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Rotary Engine Performance Computer Program (RCEMAP and RCEMAPPC)

User's Guide

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I ABSTRACT

This report is a user's guide for a computer code that simulates the performance of several rotary combustion engine configurations. It is intended to assist prospective users in getting started with RCEMAP and/or RCEMAPPC. RCEMAP (Rotary Combustion Engine performance MAP generating code) is the mainframe version, while RCEMAPPC is a simplified subset designed for the personal computer, or PC, environment. Both versions are based on an open, zero-dimensional combustion system model for the prediction of instantaneous pressures, temperature, chemical composition and other in-chamber thermodynamic properties. Both versions predict overall engine performance and thermal characteristics, including bmep, bsfc, exhaust gas temperature, average material temperatures and turbocharger operating conditions. Required inputs include engine geometry, materials, constants for use in the combustion heat release model and turbomachinery maps. Illustrative examples and sample input files for both versions are included.

II INTRODUCTION

This guide is intended to assist prospective users in getting started with **RCEMAP** and/or **RCEMAPPC**. These are two closely-related versions of a computer code to simulate the performance of several rotary combustion engine (RCE) configurations. **RCEMAP** is the mainframe version, while **RCEMAPPC** is a simplified subset designed for the personal-computer or PC environment. To avoid duplicate discussions of these generally-similar codes, **RCEMAP** is presented in the main text below, while **RCEMAPPC** is described in Appendix A. Both versions are based on an open, zero-dimensional combustion system model for the prediction of instantaneous pressures, temperatures, chemical composition and other in-chamber thermodynamic properties. Both versions predict overall engine performance and thermal characteristics, including bmep, bsfc, exhaust gas temperature, average material temperatures and turbocharger operating conditions. Required inputs include engine geometry, materials, constants for use in the combustion heat release model, and turbomachinery maps. Illustrative examples and sample input files for both versions are included.

This report is a user's guide. It's only purpose is to get the prospective user "up-and-running" as quickly as possible. In that spirit, the basic principles of rotary engine operation are not reviewed herein, but can be found in books by Yamamoto (1)* and Heywood (2) as well as other books and papers. Similarly, the detailed development of equations and algorithms is not recounted in this guide. However, for the benefit of those who may need to modify the program, Appendix B does present the main equations used, and the source codes are extensively commented. Many prior contributions are pointed out, either in Section III-F below (Code History) or within the comments to the source code listings.

II-A Mainframe Code

The mainframe version of the code (**RCEMAP**), which receives primary emphasis herein, was developed in a VAX 8600 VMS mainframe environment and requires that or an equivalent class of computing system to run successfully. A description of the scope of **RCEMAP** is presented first. Next, there is a section on running **RCEMAP**, including three examples, a flow chart and a discussion of errors the user may encounter. Comprehensive tables of inputs and outputs follow the section on running the code and finally, several more examples are provided. Throughout the guide are sample input and output files.

There are seven examples in this guide, six of which apply directly to the mainframe version. In the first of those examples, a naturally aspirated 36 cubic inch engine is run at 7000 rpm and medium load at sea level. For the second example, the same engine is run at various speeds and loads and an engine map is plotted. The third example is for a turbocharged engine run at 7000 rpm. The fourth example run produces an engine map for a supercharged engine. In the fifth example, the same turbocharged engine as in the third example is run at various loads and speeds. Finally, a two-stage-

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* Numbers in parentheses denote references, given at the report's end

compression turbocharged engine is run at 7500 rpm from sea level to 25,000 ft and the power and fuel consumption are plotted as functions of altitude. These examples cover the range of engine configurations modeled in **RCEMAP**. (With input format conversion, the same examples could be run with **RCEMAPPC** to yield substantially similar results.)

II-B PC-Compatible Code

A simplified, DOS-compatible, PC-based version of the code known as **RCEMAPPC** has also been developed. This brings most of the capabilities of the mainframe code to the widely-available PC environment. **RCEMAPPC** and the principal differences between it and the mainframe version are described in Appendix A of this report. Differences are also summarized in the following text. The reader is cautioned that Appendix A is not self-contained, but rather assumes prior familiarity with the general flow and at least the input and output files of **RCEMAP**. Appendix A also includes a seventh and final example to illustrate the code's use in the DOS environment.

There are several differences between the two versions. The first of these is simply a bookkeeping issue: **RCEMAP** uses the NAMELIST input format. **RCEMAPPC** does not currently support this feature, but rather uses conventional, formatted read statements. (Hence the earlier remark about input format conversion.)

A more substantive and technical issue concerns the gas exchange process model which couples the RCE to the turbomachinery. i.e., the cycle simulation inherently includes two major groups of computations: one describing the RCE core; and the other describing the turbomachinery. The gas-dynamic coupling between these dissimilar groups of machinery is all-important. In **RCEMAP**, a dynamic, emptying-and-filling model results in mutual boundary conditions which vary throughout the cycle. As a result, the core engine and turbomachinery sections of the code must be iterated together. This is an easy task for a mainframe, but in the present formulation it exceeds the conventional memory limitations of the typical, DOS-based PC (<640 Kb). In **RCEMAPPC**, a simpler though arguably less realistic model based on the "infinite-plenum" assumption was used. This model results in constant boundary conditions, so that the two major technical sections can be decoupled and solved independently. (Each section is consistent with DOS memory limitations.) An external iteration loop is then used to balance the plenum conditions, so that core engine and turbomachinery gas flow requirements are both satisfied at the same time. While perhaps less accurate, this approach has a substantial side benefit in addition to DOS and PC compatability. I.e., the core engine and the turbomachinery sections can be run separately to produce useful information. For example, by specifying the plenum conditions as atmospheric, the core section alone will provide the naturally-aspirated performance level of a rotary engine at any altitude.

Other differences involved the deletion of several seldom-used features from **RCEMAP**. This was to avoid unnecessary cross-couplings and to insure that the core engine section would fit into DOS memory.

III SCOPE

This section of the guide is written to expose the user to the scope of problems addressed by RCEMAP/RCEMAPPC and to preview the input and output data. Previous work on RCEMAP is also recognized and other sources of information are presented.

Mainframe users are advised to first read Section IV and work through the examples included. Next, read Section V to better understand code options and inputs. Finally, Section VI tells the user where to find program outputs and how to interpret them. The PC user is also advised to begin with Sections IV, V and VI, even though the sample files included therein cannot be used directly by RCEMAPPC. Then, keeping in mind that RCEMAPPC is a subset of RCEMAP, read Appendix A to understand the similarities and differences between the two versions and work through the final example provided.

It is strongly recommended that the user eventually read the entirety of this report. Many facets of the model are subject to constraints or limitations and may not predict engine performance well when not used properly. In addition, output data can be difficult to interpret without a knowledge of just how they were generated.

The following remarks apply generally to both versions of the code; however, it should be recalled that the data files mentioned prior to Appendix A are NAMELIST-formatted specifically for RCEMAP and cannot be read by RCEMAPPC.

III-A Code Scope

RCEMAP can analyze several RCE configurations. These configurations can include single or multiple rotors, one of four turbo machinery and intake/exhaust configurations and can be made of any suitable material for which the thermal properties are known. The four possible turbomachinery and intake/exhaust configurations are illustrated in Figure III-1. (Figures and Tables are grouped at the end of each major Section.)

The simplest configuration is the naturally aspirated direct injection stratified charge (DISC) engine (Figure III-1(a)). For such a system, the user provides the intake manifold pressure and temperature and the exhaust manifold pressure. These properties do not vary during the cycle. Thus, the results from RCEMAP and RCEMAPPC are identical for this case.

A supercharged engine is shown in Figure III-1(b). The user may supply compressor maps to specify the compressor performance or employ steady mass, constant temperature flow from the compressor to the intake manifold. If compressor maps are used, an aftercooler may be used as well. Pressure and temperature drops across the aftercooler are calculated internally.

Figure III-1(c) is a turbocharged wastegated DISC rotary combustion engine. Compressor and turbine performance is specified one of two ways. Either performance maps are used or the flow rate from the compressor to the intake manifold and from the exhaust manifold to the turbine is assumed constant during the cycle. The wastegate is simply an orifice of specified area and discharge coefficient open to an infinite plenum. Flow through the wastegate is 1-D, compressible and quasi-steady.

Finally, the most complex system which can now be analyzed with `RCEMAP` is the two-stage-compression turbocharged wastegated DISC RCE (Figure III-1(d)). Both compressors are attached to the same shaft as the turbine and run at the same actual shaft speed. An intercooler can be placed between the two compressors. The user specifies the intercooler pressure drop, the heat transfer coefficient and the frontal area of the coolant passages in the flow.

There is a less developed version of `RCEMAP` for a carbureted RCE. Currently, there are no supercharging or turbocharging options in the carbureted engine code. However, these options are not fundamentally different from the versions for a DISC engine and should not be hard for an intrepid programmer to add.

III-B Ground Rules

To prevent confusion, the authors will state several conventions used in this report. The top center (TC) rotor position is shown in Figure III-2(a). In this position, the chamber of interest (the shaded area) has the minimum area or volume and is adjacent to the spark plug. Figure III-2(b) illustrates the bottom center (BC) position. The rotor is again at a minimum volume position, but now adjacent to the ports.

In this report, only crank angle (with respect to TC) is used to describe rotor position, though in the literature the reader may also encounter position described in terms of rotor angle. Since the rotor completes one rotation per cycle while the crank shaft rotates three times per cycle, the rotor angle (relative to TC) is one third the crank angle. Crank angle is measured relative to TC. The top center position is assigned a crank angle of 0 degrees. The crank angle 30 deg after top center (ATC) is written either 30 deg ATC or 30 deg. The crank angle 30 deg before top center (BTC) is written either 30 deg BTC or -30 deg. BC alternatively is denoted -540 deg, 540 deg BTC, 540 deg or 540 deg ATC.

The engine cycle begins when the lead apex seal just begins to uncover the intake port (Figure III-2(c)) and ends 1080 deg later, when the rotor has made a full revolution. The intake process lasts until the lag apex seal just closes the intake port. Compression follows intake and lasts until the spark fires. Combustion/expansion follows compression and ends when the lead apex seal reaches the exhaust port. Finally, exhaust lasts from the time the lead apex seal reaches the exhaust port until the lag apex seal passes beyond the exhaust port. Note that there is a substantial overlap period for the intake and exhaust processes.

III-C Inputs

One benefit of `RCEMAP` is its ability to predict engine performance given limited engine data. However, the more information provided to the code, the more accurate its predictions can be. `RCEMAP` inputs are divided into six categories: engine configuration and geometry; operating conditions; heat transfer parameters; combustion parameters; friction parameters; and mathematical constants governing code flow. The user has the option of providing inputs or relying on default values. Below are general descriptions of the six `RCEMAP` input categories. More detailed descriptions of numerous inputs are provided in section V of this report. Tables V-1 – V-61 are comprehensive tables of program inputs.

To configure an engine, the user must specify whether the engine is naturally aspirated, supercharged, turbocharged or turbocharged with two stages of compression. Two logical variables (`LTCHAR` and `L2C`) determine the type of turbocharging. For turbocharged engines, turbomachinery performance is specified via performance maps or approximate means. In addition to turbomachinery performance, intake and exhaust manifold volumes must be specified for a turbocharged engine. To specify RCE geometry, the user inputs eccentricity, rotor radius, chamber depth, rotor pocket volume, trochoid housing oversize and rotor tip clearance. Finally, turbomachinery and engine communicate through intake and exhaust ports. Port inputs are areas, opening and closing crank angles and discharge coefficients.

In addition to intake and exhaust configuration, the user can specify component materials and cooling characteristics. Options include user-input steady component temperatures, user-input component temperatures which vary with crank angle and internally calculated component temperatures based on 1-D conduction and average chamber gas properties. These options allow the user to use experimental data as component temperature data, to run a hypothetical adiabatic engine or to run a hypothetical zero heat transfer engine, among other options. The only cooling schemes available are liquid cooled trochoid housing, air cooled side housings and oil spray cooled rotor. Component cooling is summarized in Figure III-3.

Heat transfer inputs vary according to how component temperatures are calculated. The user either provides wall temperatures or information about the component materials, such that temperatures are calculated internally. For user-input wall temperatures, the user specifies trochoid housing, rotor face and side housing temperatures. Otherwise, the user specifies material properties including wall thickness and thermal conductivity. Regardless of the heat transfer model, the user specifies constants to calibrate the in-chamber heat transfer coefficient.

There are few inputs to the combustion model so these inputs are especially important. First, the user sets the fuel/air equivalence ratio, ϕ. The program is inaccurate when $\phi > 0.9$. Next, the user sets heat release rate parameters. As described in Appendix B, the user supplies a maximum normalized combustion heat release rate and a crank angle at which this maximum rate occurs.

A dependable method for determining the maximum normalized heat release rate is to perform a heat release rate analysis, as those of Gatowski (3), Roberts (4) or Dimplefeld (5). These analyses deduce crank-angle-by-crank-angle combustion heat release rate from engine pressure data. In the absence of engine pressure data, the user must estimate the heat release rate parameters. Because engine speed and equivalence ratio influence the combustion process, it may be necessary to adjust the heat release rate parameters for speed or mixture changes.

Friction inputs mainly describe the geometries of the apex seals, the side seals and the oil rings. For all the seals, inputs include the seal dimensions, spring forces below the seals and sliding coefficients of friction. Because the force of the apex seal against the trochoid housing has a component due to centrifugal force, an estimate of apex seal mass is also required.

Finally, numerous mathematical constants govern the program's flow. Among these, the user can supply the maximum number of cycles and the convergence criteria.

III-D Outputs

RCEMAP produces two types of performance data: crank-angle-by–crank-angle performance (e.g., chamber pressure traces or compressor flow rate histories) and cycle averaged performance (e.g., brake mean effective pressure (bmep) or volumetric efficiency). Generally, crank-angle performance is output to plot files as columns of data and cycle averaged performance parameters are output to text files which are easier to interpret. The current section of this report is intended to help the reader know whether RCEMAP is an appropriate tool for his/her applications. A comprehensive list of program outputs is presented in Tables VI-7 – VI-17.

In-cylinder thermodynamic properties, manifold thermodynamic properties and turbomachinery performance are calculated at regular crank angle intervals by RCEMAP. With these data, the user can make plots including P-V diagrams, pressure traces, chamber gas temperature histories, burning rate profiles (or heat release rate profiles) and plots of flow rates through the intake and exhaust ports. Intake and exhaust manifold pressure, temperature and mass can be plotted against crank angle as well. Turbocharged RCEMAP calculates the compressor and turbine corrected flow, corrected speed and efficiency. Heat transfer related quantities are calculated on a crank-angle basis as well. Examples include local trochoid housing wall temperatures, gas velocity (including a combustion turbulence term) and rate of energy transfer to the coolant.

A wide range of cycle-averaged performance parameters are output to text files. They are grouped into four categories: engine output parameters, heat transfer parameters, mass flow parameters and turbomachinery parameters. Among engine output parameters are indicated, brake and friction mep and power, time-averaged and mass-averaged exhaust gas temperature, thermal efficiency and brake specific fuel consumption (bsfc). Heat transfer parameters include cooling load from the trochoid housing, the rotor and the side housing, rotor, side housing and trochoid housing surface temperatures and fraction of the fuel energy lost to cooling. Air and fuel flow rate to all rotors, volumetric and trapping efficiency and trapped air mass when the intake port closes are three mass flow parameters provided by RCEMAP. Finally, cycle-averaged turbomachinery performance outputs include average compressor and turbine pressure ratio, efficiency and power required/delivered and turbocharger speed.

III-E A Preview of the Solution

The geometry of a rotary engine (without manifolds or turbomachinery) is shown schematically in Figure III-4. Only one chamber is analyzed by RCEMAP; the chamber pressure, temperature and composition for the leading and trailing chambers are taken from stored data. The control volume (dotted line) is treated as an open thermodynamic system. Mass crosses the system boundaries via the intake port (a), the exhaust port (b), the fuel injector (c) or as leakage and crevice flows at the seals (d and e). All leakage and crevice flows are lumped at the apex seals, though, in the real case, leakage occurs through the side seals and crevice flows may occur at the spark plug hole, the injector tip or along the side seals. For the DISC engine, it is assumed the gas in the control volume has uniform pressure, temperature and composition throughout the cycle (properties do, however, vary with crank angle).

Combustion is modeled in RCEMAP via an empirical heat release rate function developed for direct injection stratified charge combustion by Gatowski et al. (3). The fuel energy release rate has two stages: a linear rise to a maximum value, followed by an exponential decay, as shown in Figure III-5. This burn rate profile was formulated to best fit burn rates calculated using experimental pressure profiles for DISC engines. In RCEMAP the user specifies the burn rate by providing a normalized maximum heat release rate and the crank angle for the maximum heat release rate.

A Woschni function (6) is employed to calculate the heat transfer between the chamber gas, the trochoid housing, the side housing and the rotor face. As mentioned above, the trochoid housing, the side housing and the rotor face surface temperatures are either specified by the user or calculated internally based on 1-dimensional quasi-steady heat transfer. Figure III-6 shows the path for heat transfer to the trochoid housing coolant. The housing is made of up to three materials of differing thermal conductivities. The heat transfer coefficient on the gas side is calculated with a Woschni function. The heat transfer coefficient on the coolant side is calculated based on flow in a pipe and allows for nucleate boiling. The user must provide the coolant side heat transfer coefficients for the side housing and rotor. The side housing is air cooled and the rotor is cooled by an oil spray. Surface temperatures for the two housings are calculated at 30 crank angle positions, based on average gas temperatures and heat transfer coefficients "seen" by these positions.

Like the combustion chamber, intake and exhaust manifolds are modeled as open thermodynamic systems with uniform temperature, pressure and composition (simple emptying and filling model). Schematics of the intake and exhaust manifold models are given in Figure III-7. Greater accuracy in prediction of manifold behavior might be possible through use of Pearson's (7) or Chapman's (8) one-dimensional manifold models. Some one-dimensional models are billed as fast, as well as accurate.

Steady flow maps specify the performance of turbomachinery in RCEMAP. Because the actual conditions under which the compressor and especially the turbine operate are unsteady, some error results. However, a more complex turbomachinery analysis is not consistent with the complexity of the rest of the program. One alternative the authors are pursuing is to scale existing turbine maps to include unsteady effects. The turbocharger is assumed to operate at constant actual speed throughout each engine cycle due to the turbocharger's inertia. At each crank angle, the program calculates the turbine and compressor referred speed. Since the pressure upstream of the compressor and downstream of the turbine are specified and the intake and exhaust manifold pressures are known, the compressor and turbine pressure ratios can also be calculated. Knowing the pressure ratio and referred speed, the referred flows through the compressor and turbine are calculated.

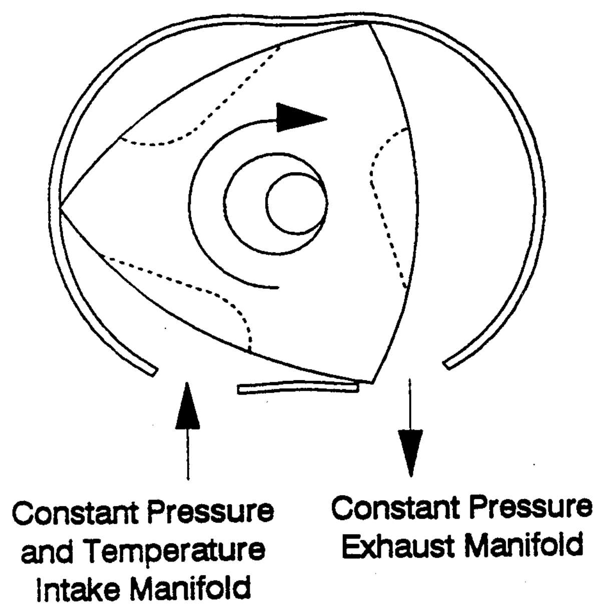
Hopefully, the reader has a general idea of how RCEMAP models a rotary engine after reading this section. For readers interested in more than a glance at the solution, Appendix B contains a fairly detailed description.

III-F Code History

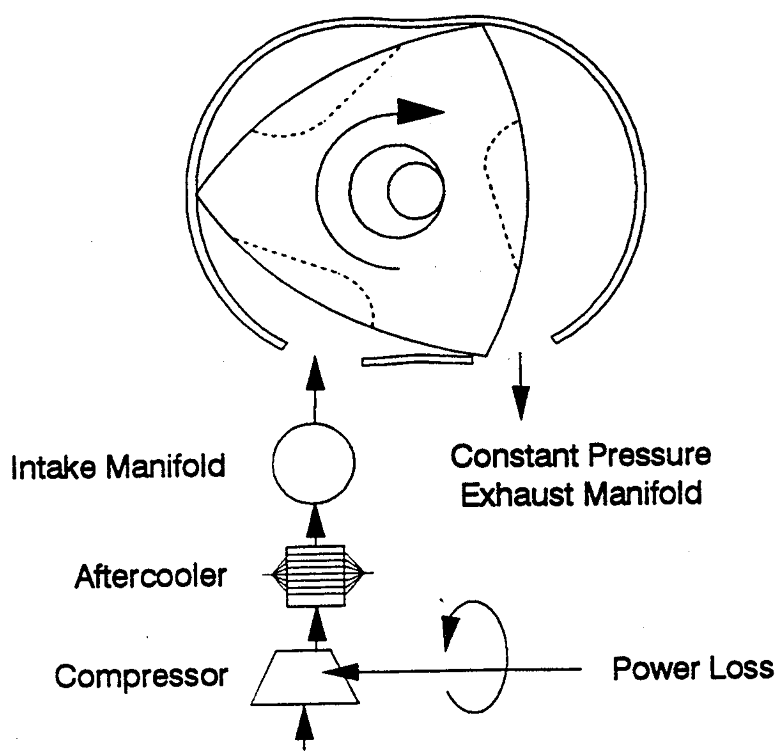
Initial development of RCEMAP (originally called the MIT code) took place at the Massachusetts Institute of Technology's Sloan Automotive Laboratory between 1983 and 1987. The work was funded by a NASA grant and was under the direction of Prof. J. Heywood. Norman (9) converted a four-stroke crank-piston carbureted engine model to the rotary engine geometry. In his thesis he addresses crevice and leakage flows and heat transfer in detail. The burning process is modeled as a Wiebe function in the original, carbureted engine model. To convert the carbureted engine to DISC operation, Roberts (10) substituted the DISC combustion model of Gatowski et al. (3) for the Wiebe function and altered the calculation of gas thermodynamic properties. Roberts' thesis also describes a procedure for calculating fuel energy release rate for experimental chamber pressure data. Stanton (11) added options to the MIT code which enabled user-input housing surface temperatures and performed a parametric study on a hypothetical engine, illustrating the influence of housing material type and heat transfer on engine performance.

Since 1983 the code has undergone changes in turbomachinery, manifold, heat transfer and friction modeling at the NASA Lewis Research center, Michigan State University and John Deere Technologies International Inc., Rotary Engine Division. The MIT code (unchanged) was run for an Outboard Marine Company experimental DISC RCE and results were published in a SAE paper by Nguyen et al. (12). Bartrand and Willis made numerous additions to the program including one-dimensional heat transfer, manifold models and turbomachinery. Some results from an early version of the program are found in reference (13). Seal friction subroutines were added to RCEMAP by Rachel et al. (14). Dimplefeld and Hoque (15) made several additions including provisions for tip clearance and trochoid housing oversize in the geometry routines, improved estimates of ancillary losses and trouble shooting.

Willis and Bartrand converted of RCEMAP to RCEMAPPC during the preparation of this document. As described above, RCEMAPPC is based largely upon RCEMAP principles; however, a new protocol for executing the program within PC limitations had to be developed. There are currently no other references available for RCEMAPPC.

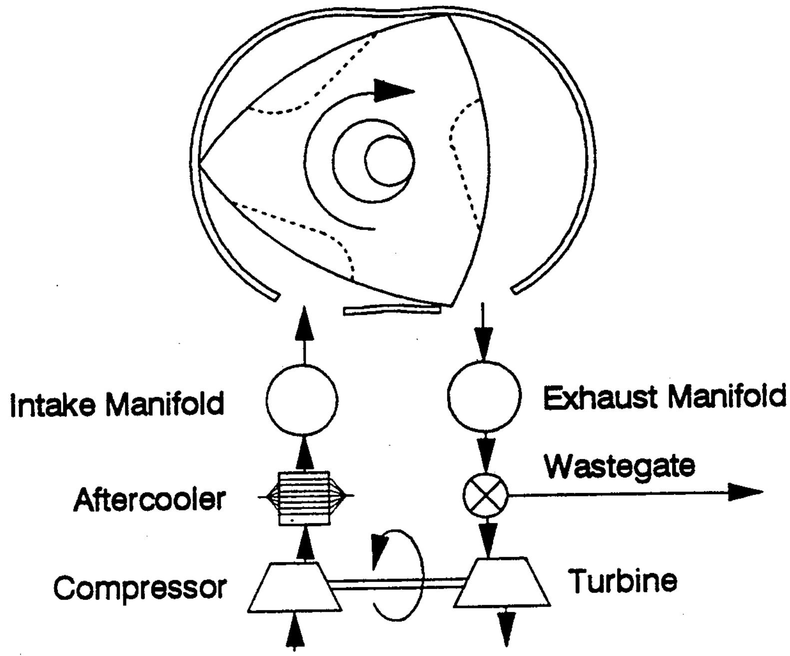


(a) Naturally Aspirated RCE

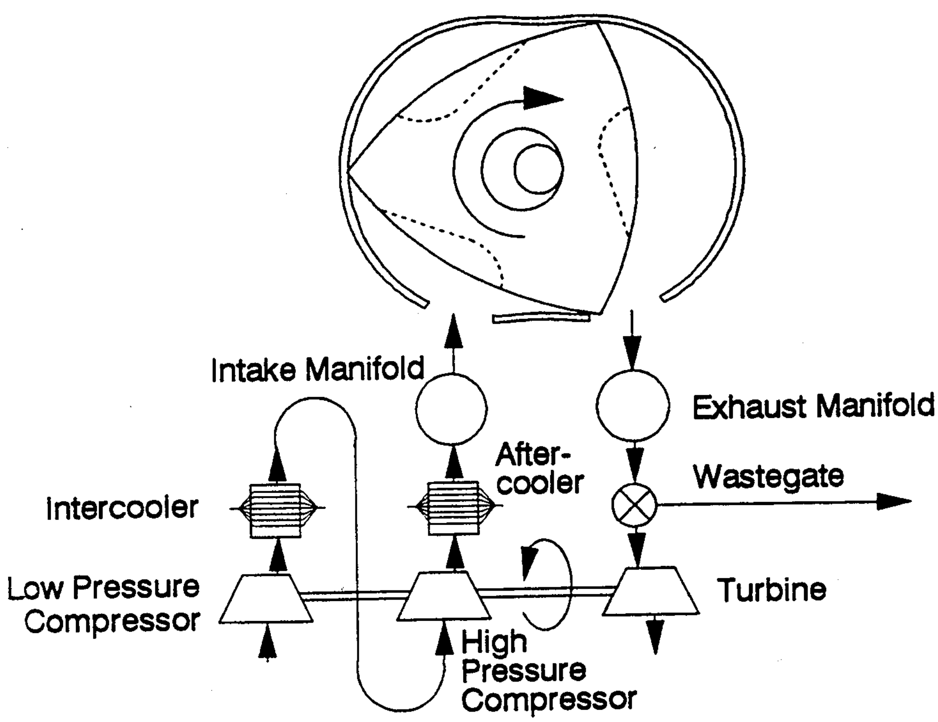


(b) Supercharged RCE

Figure III-1: Engine Configurations

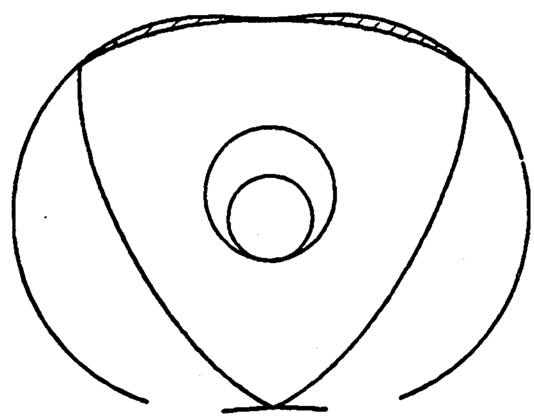


(c) Turbocharged RCE

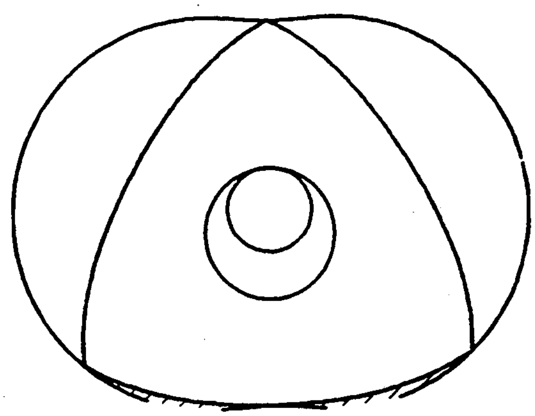


(d) Two-Stage Compression Turbocharged RCE

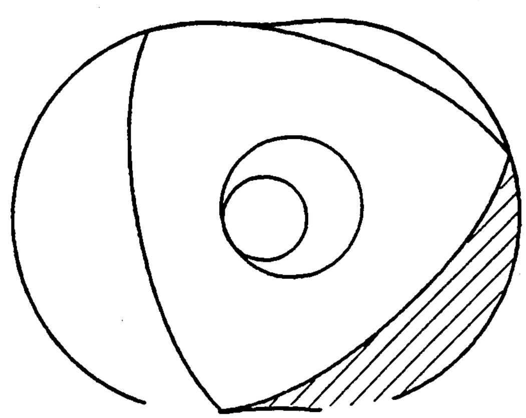
Figure II-1: Engine Configurations



(a) Top Center

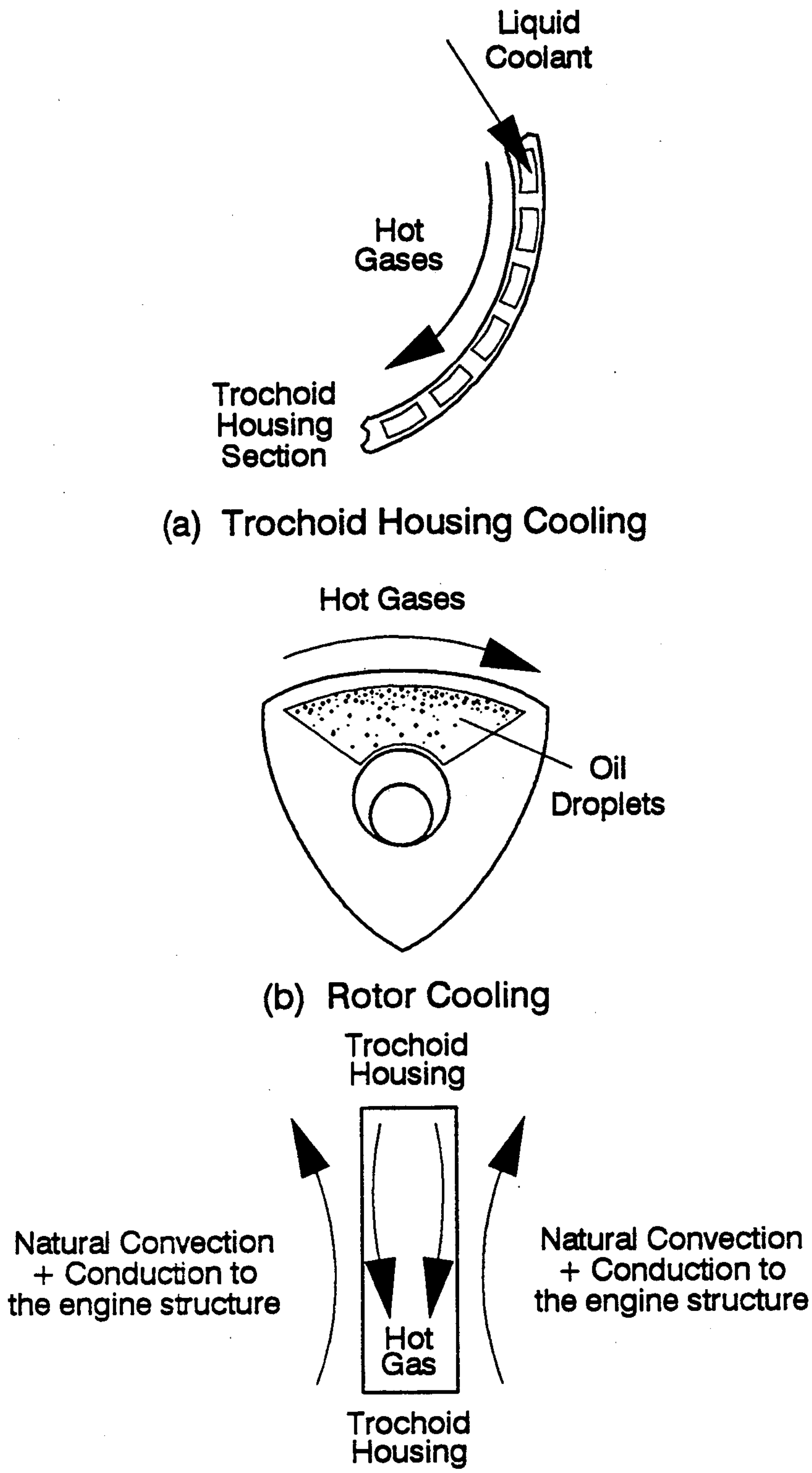


(b) Bottom Center



(c) At the Start of Intake

Figure III-2: Rotor Position



(a) Trochoid Housing Cooling

(b) Rotor Cooling

(c) Side Housing Cooling

Figure III-3: Cooling

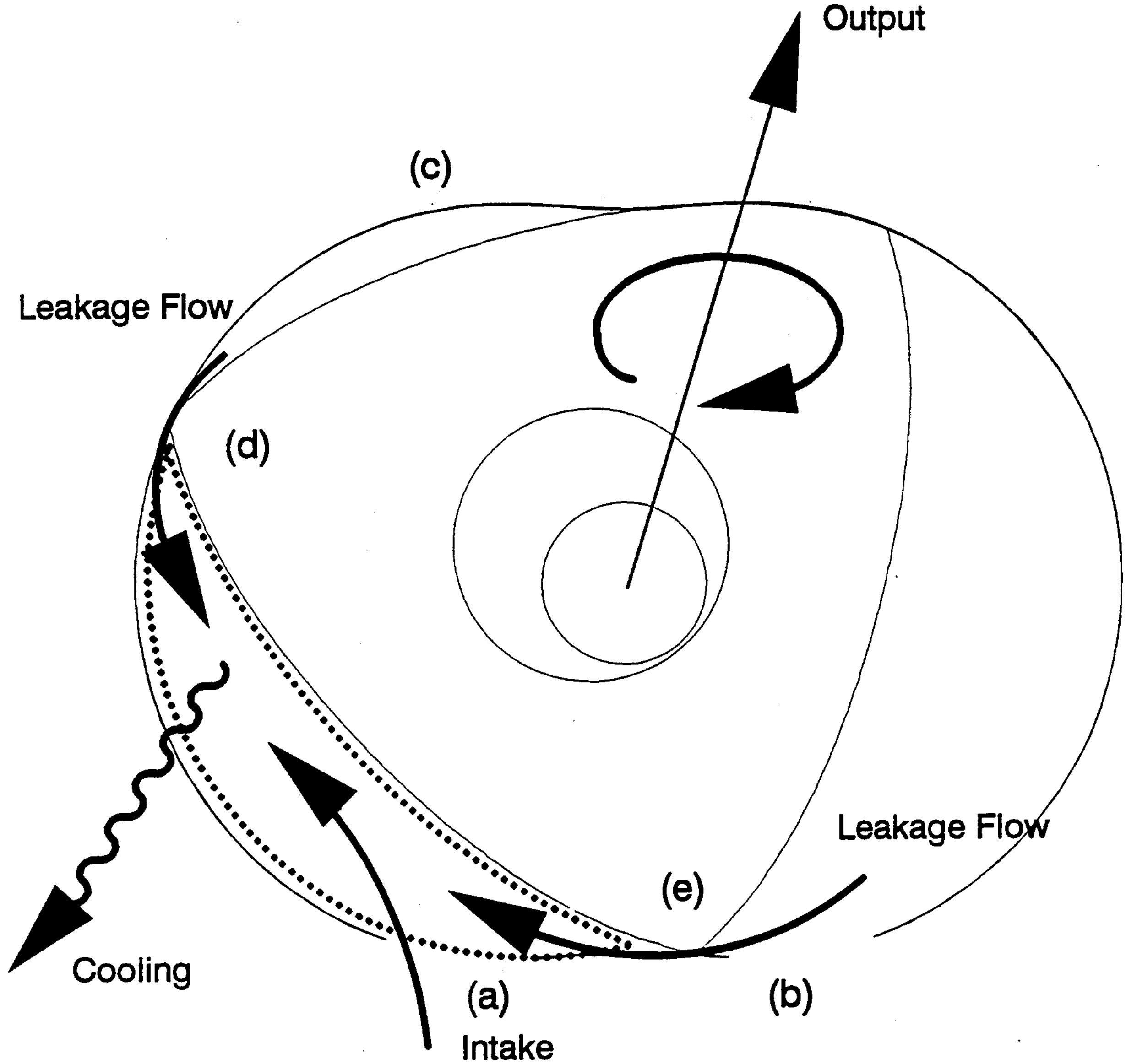


Figure III-4: The Combustion Chamber as an Open Thermodynamic System

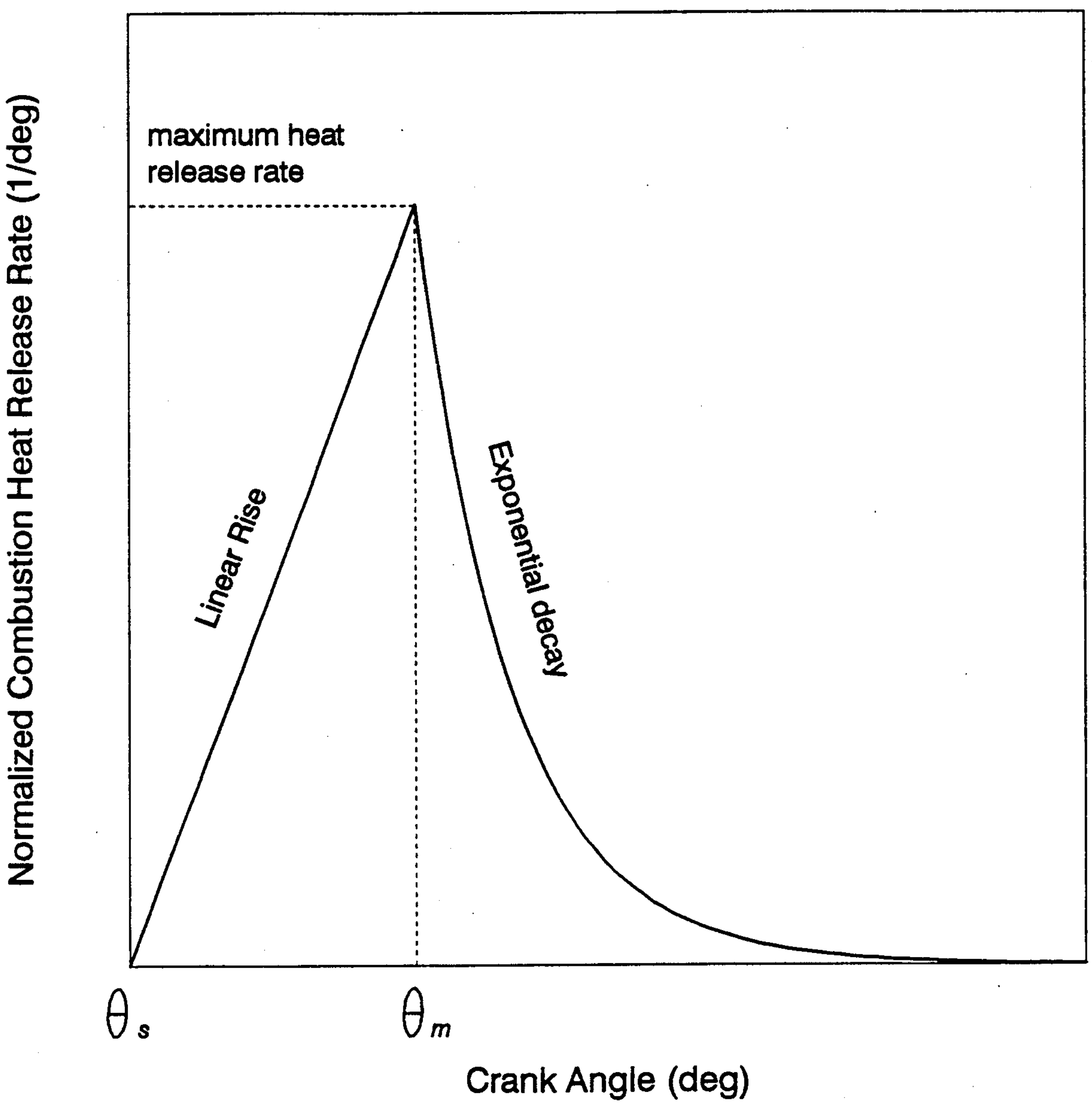


Figure III-5: Fuel Energy Heat Release Rate

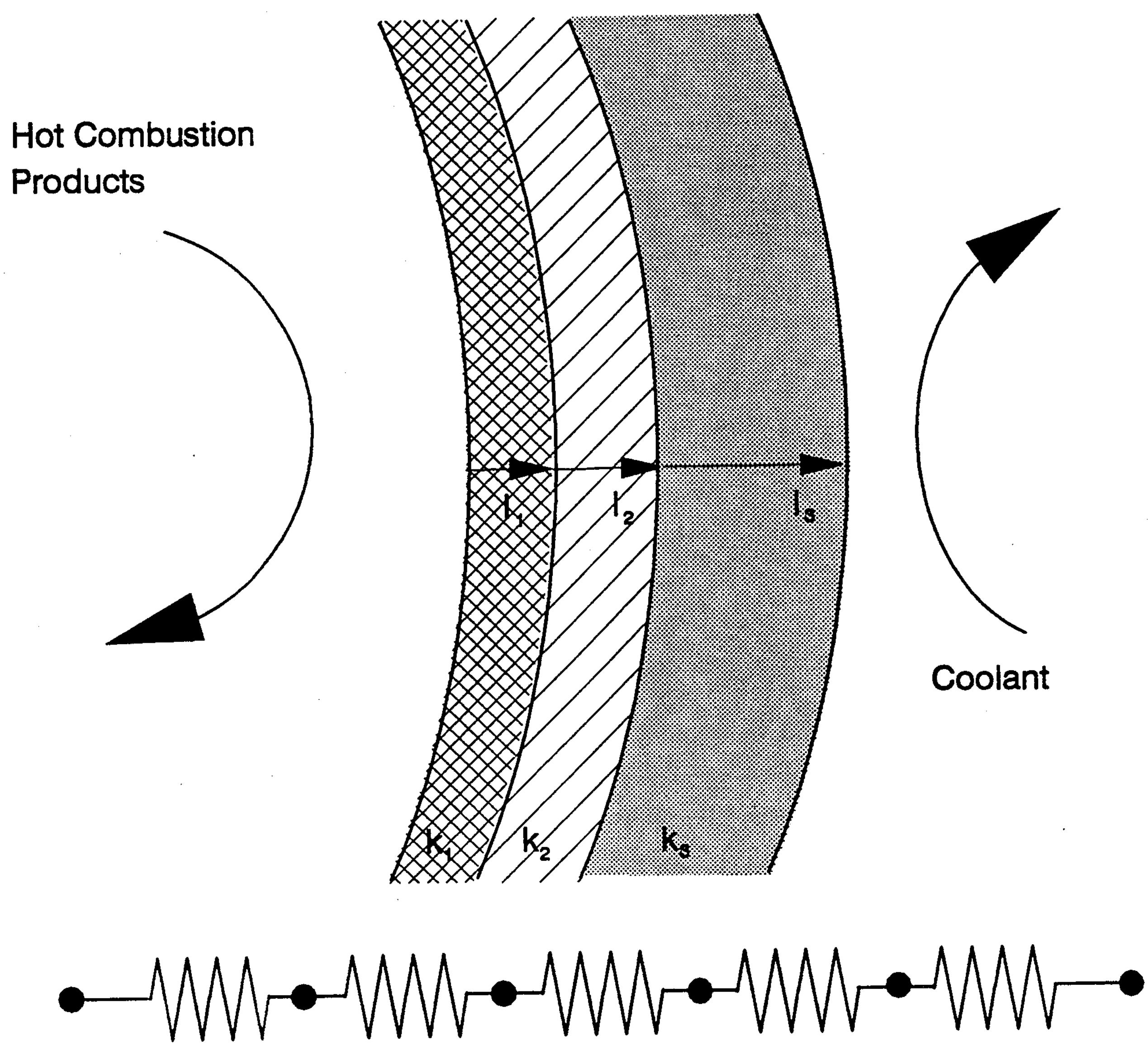
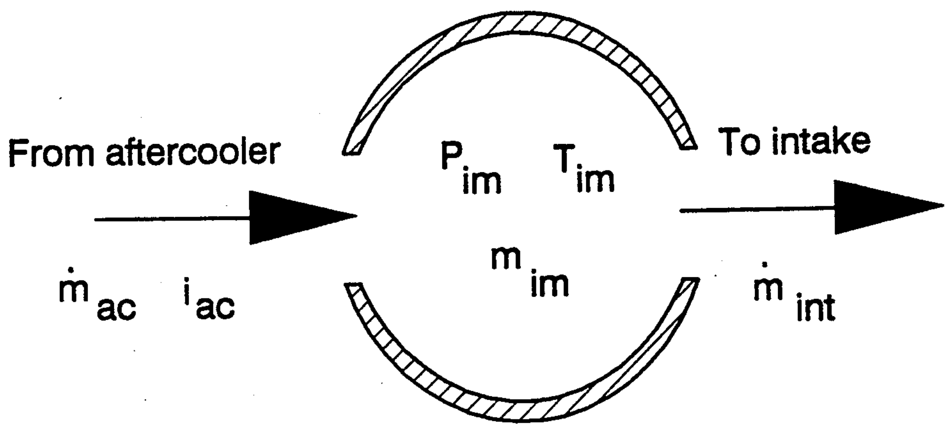
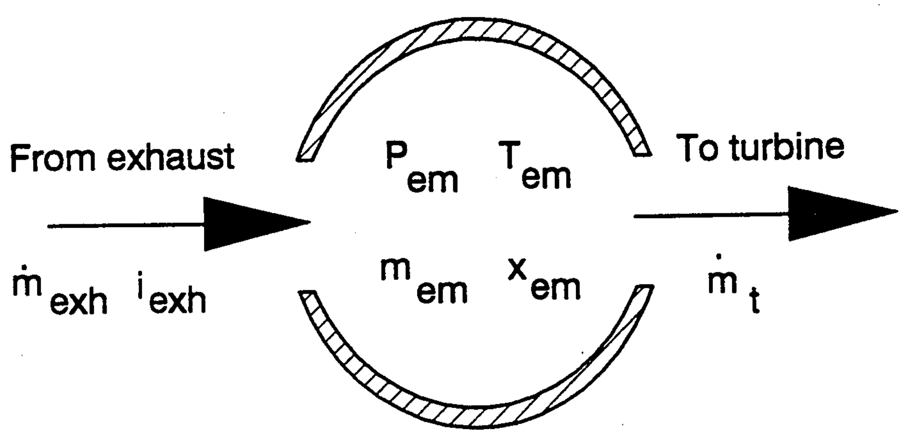


Figure III-6: One-Dimensional Heat Transfer Model



(a) Intake Manifold



(b) Exhaust Manifold

Table III-7: Manifold Models

IV RUNNING RCEMAP

As might be expected of the software developers, the authors consider RCEMAP an easy code to run. All input data are in namelist form, with the exception of turbomachinery performance maps. For many variables, there are internal traps to weed out bad inputs. When execution is halted short of a solution, an explanation and suggestions for recovery are often presented. On the other hand, RCEMAP requires numerous inputs and is long enough to make debugging difficult.

To run RCEMAP, the user sets up an executable version, fills the appropriate input files with data, creates any necessary output files and runs the program. To obtain a single operating point for a naturally aspirated engine takes about 2 min of CPU time on a VAX 8600 mainframe computer. A single operating point for a turbocharged engine may take 5 min on the VAX 8600. If a single case takes more than 10 min on the VAX 8600, something has probably gone wrong and the user is advised to abort the run.

This section of the report describes how to run RCEMAP. First there is a brief section on program flow, including a flowchart. Next there is a description of the files needed for various cases. Then there is an example case. Finally, error conditions are discussed.

IV-A Program Flow

One can think of RCEMAP as consisting of two pieces: a driver routine and a cycle simulation. (As previously noted, the cycle simulation can be further subdivided into core engine and turbo machinery sections; this is unnecessary however with mainframe memory capabilities.) The driver routine runs the cycle simulation for various engine speeds, loads and altitudes. After the driver routine obtains solutions at all specified loads, speeds and altitudes, engine maps are written to output files. These maps give the variation of power, specific fuel consumption, exhaust gas temperature, cooling load, air flow rate, fuel flow rate, intake manifold pressure, intake manifold temperature and exhaust manifold pressure as functions of engine load, speed and altitude. Numerous other outputs are generated during RCEMAP's execution.

The cycle simulation steps through an engine cycle, crank-angle-by-crank-angle. At the end of the engine cycle the chamber pressure, temperature and various other quantities are compared to their beginning values. If the beginning and ending values are close enough, the solution is converged. Figure IV-1 is an abbreviated flowchart for RCEMAP.

IV-B What Files Are Needed ?

To run RCEMAP, the user needs an executable (FORTRAN) version of the code and various input and output files. Which files are necessary is determined by the way wall heat transfer is calculated and whether the engine is turbocharged.

In all cases, the files RCEMAP.INP, ROTARY.INP and RCEMAP.OUT must be present to run RCEMAP. File RCEMAP.OUT may be empty, but must exist, since its status is 'OLD' in its OPEN statement. In addition. there must also be output files corresponding to each .TRUE. value of variable LDEBUG in file ROTARY.INP. The output files are listed in Table V-20 and described in section VI.

Heat-transfer-related inputs are described in detail in section V-B. If the user wishes the program to calculate the trochoid housing wall temperatures internally, he/she must set IHTPRO in ROTARY.INP equal to 3 and provide file HHEAT.INP. Otherwise, HHEAT.INP is not needed. The contents of file HHEAT.INP are presented in Tables V-43 – V-49. Likewise, if the user wants internally calculated side housing wall temperature, file SHEAT.INP must be provided and ISTPRO of ROTARY.INP must equal 3. The contents of SHEAT.INP are provided in Tables V-50 – V-54. Finally, for internally calculated rotor face temperatures, let IRTPRO equal 3 and provide file RHEAT.INP. The contents of RHEAT.INP are listed in Tables V-55 – V-59.

The user must provide input file TURB.INP when RCEMAP simulates a turbocharged engine. The contents of TURB.INP are described in section V-C. To simulate turbocharger operation, RCEMAP interpolates compressor and turbine flow and efficiency maps. Because turbocharger operation influences engine operation and vice versa, turbocharged engine cases take more cycles to converge than naturally aspirated or supercharged engines.

IV-C Examples

Two simple examples are now presented. The user is advised to run these cases and compare his/her output with the listings in Tables IV-3, IV-4, IV-6 and IV-7 before trying more complex cases. By doing this, the user not only gains experience running the program, but also identifies any incompatibilities the code may have with his/her particular operating system or version of FORTRAN. As of the writing of this guide, RCEMAP has been run extensively on a VAX 8600 mainframe computer. It has also been run on a SUN workstation and an IBM mainframe computer.

The first case (example 1) generates performance data for a naturally aspirated 575 cc (35.2 cu in) single rotor engine at a single operating condition. Engine speed is 7000 rpm, equivalence ratio is 0.6 and the altitude is sea level. Trochoid housing temperature is 450 K (350 deg F), side housing temperature is 400 K (260 deg F) and rotor face temperature is 500 K (440 deg F). Component temperatures do not vary during the cycle. Input file RCEMAP.INP is listed in Table IV-1. Input file ROTARY.INP is listed in Table IV-2. No other input files are needed. There should be two output files in the user's work area: RCEMAP.OUT and RSHORT.OUT. Files RCEMAP.OUT and RSHORT.OUT for this case are shown in Tables IV-3 and IV-4, respectively. RCEMAP's execution took 1 min 24.64 seconds of CPU time on a VAX 8600 mainframe computer.

For the second case, (example 2) an engine map is generated for the same engine. The naturally aspirated, single rotor engine is run at sea level at speeds from 3000 to 7000 rpm and equivalence ratios from 0.35 to 0.75. Input file ROTARY.INP does not change from the first case. The new file RCEMAP.INP is shown in Table IV-5. The second case took 21 min 18.83 seconds of CPU time on a VAX 8600 mainframe computer. Output file RCEMAP.OUT is shown in Table IV-6. Output file RSHORT.OUT was not included in this section because it was very long. Figure IV-2 shows the engine map generated for example 2. Only the data were generated by RCEMAP; RCEMAP does not include graphics routines. A useful addition to RCEMAP would be a plotting package to generate figures such as Figure IV-2.

IV-D **Pitfalls**

Sometimes RCEMAP cannot produce a solution. This may be because the user has given an unrealistic input, because an iteration in the program cannot find a root or because engine components are incompatible. In many cases the program writes an error message to the screen when execution cannot continue. The authors attempted to provide as much input data checking as possible and make error messages as descriptive as possible. However, the user may encounter situations in which RCEMAP doesn't behave as expected. Some suggestions for dodging errors are provided in this section.

Bad Inputs

Many bad inputs are flagged at the beginning of the program. Many are not. If the program returns a message saying one of your variables is out of bounds, refer to the inputs section of this report to determine the correct bounds. There are no checks for inputs like negative distances, so the user must carefully read his/her input files before submitting a job. The authors usually assume bad inputs are at fault when RCEMAP doesn't execute properly.

Very long Run Times

There are two likely culprits for very long run times: large intake/exhaust ports and incompatible combustion heat release rate inputs.

RCEMAP contains provisions for backflow of chamber gases into the exhaust manifold. When backflow occurs, the program keeps track of how much mass went into the intake manifold and what its composition was. Additionally, when intake manifold pressure and chamber pressure are nearly equal, flow may alternate between "normal" flow into the chamber and backflow. These alternations result in very small integration time steps and very slow runs. To improve run time, the user may decrease intake port area, increase engine speed or use a different turbocharger.

Another cause for slow run times is incompatible combustion heat release rate inputs. If the user-input maximum heat release rate is too large or the crank-angle interval between the time at which combustion begins and the maximum heat release rate is too large, the program predicts extremely high gas temperature and pressure. Under these circumstances, chamber properties change very rapidly and integration slows down dramatically. See Tables V-10 and V-11 for more information on heat release rate inputs.

Turbocharger-Engine Matching Problems

The most likely reason RCEMAP halts when turbocharged engines are modeled is difficulty matching the engine and turbocharger. RCEMAP may have trouble matching the turbocharger to the engine even though the turbocharger is suited to the engine. Or, the turbocharger and engine may be incompatible. When RCEMAP has turbocharger matching trouble, it writes error messages to the screen and to file RSHORT.OUT. Usually the error messages to the screen have the cryptic messages EXECUTION HALTED AT MATCH 0005. MATCH refers to SUBROUTINE MATCH and 0005 refers to error 5 in SUBROUTINE MATCH. Other turbocharger matching errors messages include MATCH 0001 – 0006, FINDR 0001 – 0005, FINDS 0001, TURPR 0001, STARTP 0001 – 0003, COMP2 0001, and START2 0001 – 0003.

When a turbo matching error is encountered, there are three ways to overcome the error. The first and easiest way to address matching trouble is to try running the same case using different starting pressures for the intake and exhaust manifolds. If this does not succeed, the user is advised run the code as far as possible and plot operating conditions on compressor and turbine maps. The output from a matching error message should tell the user what to use for the maximum number of cycles: MAXITS. Set MAXITS equal to the value of ITERAS when the turbocharger and engine couldn't match. The dreaded third option is to reprogram SUBROUTINE MATCH to begin the matching process with a different compressor corrected speed. This option is only for dire emergencies.

Other

As more and more users run RCEMAP, it is likely that errors and/or other problems will turn up. The authors would be grateful to those users who notify them of programming errors or any other difficulties.

Table IV-1: Sample Input File RCEMAP.INP, Case 1

```
&RUNRCE
   NROTOR=1, IFUELT=1, PIM=1.0, PEM=0.95,
   NALT=1, ALTL=0., ALTH=0.,
   NRPM=1, RPML=7000., RPMH=7000.,
   NPHI=1, PHIL=0.6, PHIH=0.6
&END
```

Table IV-2: Sample Input File ROTARY.INP, Case 1

```
$NLCASE
   ICASE=1, IDAY=19, IMONTH=9, IYEAR=1991, MAXITS=10 $END
$NLOPCS
   LFIRE=.T., LTCHAR=.F., L2C=.F., IFUELT=1, EGR=0.0,
   TEGR=300., ANCIL1=0.368, ANCIL2=0.132, ANCIL3=0.0059 $END
$NLGEOM
   ECCEN=1.5, ROTRAD=10.5, DEPTH=7., VFLANK=50., SZOVER=0.08,
   CLRNCE=0.064, AREALK=0.01, CREVOL=0.4 $END
$NLHREL
   TSPARK=-10., TMAX=15., XBZERO=0.0, XBSTOP=0.98,
   DQDTMX=0.05 $END
$NLPORT
   IPA=13.8, EPA=9., CDIP=0.60, CDEP=0.65, TIPO=-620.1,
   TIPC=-240.1, TEPO=199.1, TEPC=588.5, THIPO=40.,
   THEPO=40. $END
$NLHEAT
   IHTPRO=1, IRTPRO=1, ISTPRO=1, TROTI=500., TSIDI=400.,
   THOUSI=450., CONHT=0.037, EXPHT=0.8, CON1=0.75,
   CON2=1.5 $END
$NLIMAN
   LPIM=.F., VIM=2550., TIM=310. $END
$NLEMAN
   LPEM=.F., VEM=400., PEXH=0.95 $END
$NLWRIT
   LDEBUG=.F.,.F.,.T.,.F.,.F.,.F.,.F.,.F.,.F.,.F.,
      .F.,.F.,.F.,.F.,.F., LBRIEF=.F., TPRINT=5., TPRINX=5.
   $END
$NLCONV
   TCONV=0.01, PCONV=0.01, XMCONV=0.01, TRCONV=0.01,
   THCONV=0.01, PMCONV=0.01, EMCONV=0.01 $END
&NLAPEX
   ABASE=0.18, AFRC1=0.07, AFRC2=0.13, AHEIG=0.77,
   AMASS=35.0, ARAD=0.0813, FSPRI=33.36 &END
&NLSIDE
   SIDEB=0.18, SIDEH=0.24, SIDECF=0.07, SIDEF=75. &END
&NLOILS
   SOILB=0.15, SOILCF=0.06, SOILF=22.0, SOILR=6.0,
   SOILP=2.0 &END
&EXHFL
   EPTHIK=0.25, EXHPL=10., TPOUT=300., TCONP=24.,
   EXHPEM=0.8, FEXHP=1.0 &END
&ROTORB
   NRB=2, DRB=7.81, WRB=4.50, VRB=10.4, CRB=0.01016 &END
```

```
&MAINB
   NMB=2, DMB=4.60, WMB=6.36, VMB=10.4, CMB=0.01016 &END
```

Table IV-3: Output File RCEMAP.OUT, Case 1

```
>>>>> RCE PERFORMANCE MAP ROUTINE OUTPUT



>>>>> ENGINE PERFORMANCE PARAMETERS FOR:

      INTAKE MANIFOLD PRESSURE    =     0.0000 ATM
      INTAKE MANIFOLD TEMPERATURE =   298.170 K
      EXHAUST MANIFOLD PRESSURE   =     0.9500 ATM


   >> AIR MASS FLOW RATE (LB/HR)

PHI\RPM      7000.00
--------------------

 0.600        616.04


   >> FUEL MASS FLOW RATE (LB/HR)

PHI\RPM      7000.00
--------------------

 0.600         24.10


   >> BRAKE POWER (BHP)

PHI\RPM      7000.00
--------------------

 0.600         46.45


   >> HEAT TRANSFER TO COOLANT (% FUEL ENERGY)

PHI\RPM      7000.00
```

```
--------------------

 0.600        15.79

   >> FRICTION POWER (FHP)

PHI\RPM     7000.00
--------------------

 0.600        21.79

   >> MASS AVERAGED EXHAUST GAS TEMP (DEG R)

PHI\RPM     7000.00
--------------------

 0.600      1789.01

   >> THERMAL EFFICIENCY

PHI\RPM     7000.00
--------------------

 0.600       36.456

   >> BRAKE SPECIFIC FUEL CONSUMPTION (LB/HP-HR)

PHI\RPM     7000.00
--------------------

 0.600        0.519
```

Table IV-4: Output File RSHORT.OUT, Case 1

```
>>>>>> OUTPUT FROM MIT DISC RCE PERFORMANCE MODEL

CASE  1,  19 SEP  1991


>>>>>> BRIEF ECHO OF ENGINE GEOMTERY AND OPERATING CONDITIONS

       NUMBER OF ROTORS                          =          1
       ENGINE SPEED (RPM)                        =    7000.00
       EQUIVALENCE RATIO (-)                     =      0.600
       DISPLACED VOLUME (CC)                     =     577.16
       AVERAGE INTAKE MANIFOLD PRESSURE (ATM)    =       1.00
       AVERAGE INTAKE MANIFOLD TEMPERATURE (K)   =     310.00
       EXHAUST GAS RECIRCULATION (%)             =       0.00
       AVERAGE EXHAUST MANIFOLD PRESSURE (ATM)   =       0.95
       NORMALIZED MAX COMB HEAT RELEASE RATE     =     0.0500
       ANGLE FOR MAX HEAT RELEASE RATE           =      15.00
       HEAT RELEASE RATE DECAY CONSTANT          =     7.1000
       FUEL USED IS ISOOCTANE
       INTAKE MANIFOLD PROPERTIES ARE FIXED


>>>>>> BASIC ENGINE DIMENSIONS

       NUMBER OF ROTORS                          =          1
       ECCENTRICITY (CM)                         =      1.500
       GENERATING RADIUS (CM)                    =     10.500
       ROTOR POCKET VOLUME (CC)                  =      50.00
       ESTIMATED LEAKAGE AREA (SQ CM/CHAMBER)    =      0.010
       ESTIMATED CREVICE VOLUME (CC/CHAMBER)     =      0.400
       INTAKE MANIFOLD VOLUME (CC)               =    2550.00
       EXHAUST MANIFOLD VOLUME (CC)              =     400.00
       COMPRESSION RATIO (-)                     =       7.27
       DISPLACED VOLUME (CC)                     =     577.16
                        (CU IN)                  =      35.22
       INTAKE PORT OPEN AREA (SQ CM)             =     13.800
       INTAKE PORT DISCHARGE COEFFICIENT (-)     =      0.600
       EXHAUST PORT OPEN AREA (SQ CM)            =      9.000
```

```
       EXHAUST PORT DISCHARGE COEFFICIENT (-)  =      0.650


>>>>>> SEAL DIMENSIONS AND SPRING FORCES

       APEX SEAL BASE DIMENSION (CM)           =      0.180
       APEX SEAL HEIGHT (CM)                   =      0.770
       APEX SEAL SPRING FORCE (N)              =      33.36
       APEX SEAL MASS (G)                      =      35.00
       APEX SEAL TIP ARC RADIUS (CM)           =      0.081
       APEX SEAL SLIDING COEFF OF FRICTION (-) =      0.000

       SIDE SEAL BASE DIMENSION (CM)           =      0.180
       SIDE SEAL HEIGHT (CM)                   =      0.240
       SIDE SEAL SPRING FORCE (N)              =      75.00
       SIDE SEAL SLIDING COEFF OF FRICTION (-) =      0.070

       OIL SEAL THICKNESS (CM)                 =      0.150
       OIL SEAL RADIUS (CM)                    =       6.00
       OIL SEAL SPRING FORCE (CM)              =      22.00
       CRANK CASE PRESSURE (ATM)               =       2.00
       OIL SEAL SLIDING COEFF OF FRICTION (-)  =      0.060


>>>>>> INPUT ENGINE OPERATING CONDITIONS

       EQUIVALENCE RATIO  [(F/A) / (F/A)S]     =      0.600
       ENGINE SPEED (RPM)                      =    7000.00
       CRANK ANGLE INTAKE PORT OPENS (DEG)     =    -620.10
       CRANK ANGLE INTAKE PORT CLOSES (DEG)    =    -240.10
       ANGLE FOR INTAKE PORT TO OPEN FULLY     =      40.00
       CRANK ANGLE EXHAUST PORT OPENS (DEG)    =     199.10
       CRANK ANGLE EXHAUST PORT CLOSES (DEG)   =     588.50
       ANGLE FOR EXHAUST PORT TO OPEN FULLY    =      40.00
       CRANK ANGLE COMBUSTION BEGINS (DEG)     =     -10.00
       AVERAGE INTAKE MANIFOLD PRESSURE (ATM)  =      1.000
       AVERAGE INTAKE MANIFOLD TEMPERATURE (K) =     310.00
       EXHAUST GAS RECIRCULATION (%)           =       0.00
       AVERAGE EXHAUST MANIFOLD PRESSURE (ATM) =       0.95
       FUEL USED IS ISOOCTANE
       INTAKE MANIFOLD PROPERTIES ARE FIXED
       ENGINE IS FIRED
```

>>>>>> COOLING

WOSCHNI EXPRESSION EXPONENT (-)	=	0.800
WOSCHNI EXPRESSION COEFFICIENT (-)	=	0.037
ROTOR VELOCITY COMPONENT COEFF (-)	=	0.750
COMBUST. TURBULENCE COMPONENT COEFF (-)	=	1.500
COOLANT SATURATION TEMPERATURE (K)	=	0.00
NUMBER OF COOLANT PASSAGES (-)	=	0
AVG DIAMETER OF COOLANT PASSAGES (CM)	=	0.00
THERMAL CONDUCTIVITY OF COOLANT (W/M-K)	=	0.00
NUCLEATE BOILING COEFFICIENT (-)	=	0.00E+00
SIDE HOUSING COOLANT TEMPERATURE (K)	=	0.00
SIDE COOLANT HEAT TRANS COEFF (W/M2-K)	=	0.00
ROTOR COOLANT (OIL) TEMPERATURE (K)	=	0.00
ROTOR COOLANT HEAT TRANS COEFF (W/M2-K)	=	0.00

TROCHOID HOUSING MATERIAL	THERMAL CONDUCTIVITY (W/M-K)	THERMAL DIFFUSIVITY (M/S*S)	THICKNESS (CM)
1	0.00	0.000E+00	0.000
2	0.00	0.000E+00	0.000
3	0.00	0.000E+00	0.000

ROTOR FACE MATERIAL	THERMAL CONDUCTIVITY (W/M-K)	THERMAL DIFFUSIVITY (M/S*S)	THICKNESS (CM)
1	0.00	0.000E+00	0.000
2	0.00	0.000E+00	0.000
3	0.00	0.000E+00	0.000

SIDE HOUSING MATERIAL	THERMAL CONDUCTIVITY (W/M-K)	THERMAL DIFFUSIVITY (M/S*S)	THICKNESS (CM)
1	0.00	0.000E+00	0.000
2	0.00	0.000E+00	0.000

```
     3            0.00        0.000E+00        0.000


>>>>>> BURNING RATE INPUTS

     NORMALIZED MAX HEAT RELEASE RATE (-)      =      0.0500
     ANGLE FOR MAX HEAT RELEASE RATE (DEG)     =       15.00
     DECAY CONSTANT (-)                        =       7.100
     FUEL ENERGY/CYCLE (J) (FUEL MASS X LHV)   =    1163.375


>>>>>> MATH CONSTANTS

     MAXITS                                    =           4
     TPRINT                                    =         5.0
     TPRINX                                    =         5.0
     XBZERO                                    =       0.000
     XBSTOP                                    =       0.980
     CIINTG                                    =    1.00E-04
     CCINTG                                    =    1.00E-04
     CBINTG                                    =    5.00E-05
     CEINTG                                    =    1.00E-04
     AREROT                                    =    1.00E-03
     REL                                       =    1.00E-03
     ERMAX                                     =    0.00E+00


>>>>>> CONVERGENCE SUMMARY FOR ITERATION  4 OUT OF 10 ALLOWED

     CYCLE INITIAL CHAMBER PRESSURE (ATM)      =       1.069
     CHANGE IN INITIAL PRESSURE (%)            =        0.06

     CYCLE INITIAL CHAMBER TEMPERATURE (K)     =      835.28
     CHANGE IN INITIAL TEMPERATURE (%)         =       -0.22

     AVERAGE INTAKE MANIFOLD PRESSURE (ATM)    =       1.000
     CHANGE IN AVG INTAKE MAN PRESS (%)        =        0.00

     AVERAGE EXHAUST MANIFOLD PRESSURE (ATM)   =       0.950
     CHANGE IN AVG EXHAUST MAN PRESS (%)       =        0.00
```

```
CYCLE INITIAL INT MANIFOLD PRESS (ATM)  =      1.000
CHANGE IN INITIAL INTAKE MAN PRESS (%)  =      0.00

CYCLE INITIAL EXH MANIFOLD PRESS (ATM)  =      0.950
CHANGE IN INITIAL EXHAUST MAN PRESS (%) =      0.00

CURRENT CYCLE INTAKE MASS (G)           =      0.669
CURRENT CYCLE EXHAUST MASS (G)          =      0.695
MASS LEAKED TO LEAD CREVICE (G)         =      0.000
MASS LEAKED TO LAG CREVICE (G)          =      0.000
CYCLE MASS OF FUEL INJECTED (G)         =    0.02621
INITIAL MASS IN THE CHAMBER (G)         =      0.093
DIFF IN INTAKE AND EXHAUST MASS (%)     =       0.13

MAX TROCHOID HOUSING TEMPERATURE (K)    =       0.00
MAX CHANGE IN TROCH HOUSING TEMP (%)    =       0.00
NEW ROTOR FACE TEMPERATURE (K)          =     500.00
CHANGE IN ROTOR FACE TEMPERATURE (%)    =       0.00


>>>>> SEAL AND BEARING FRICTION


    -->  FRICTION POWER, ALL APEX SEALS (3 PER ROTOR)
                              (KW)          ---->       1.645
                              (HP)          ---->       2.204
    -->  FRICTION POWER, ALL SIDE SEALS (6 PER ROTOR)
                              (KW)          ---->       1.437
                              (HP)          ---->       1.926
    -->  FRICTION POWER, ALL OIL SEALS (2 PER ROTOR)
                              (KW)          ---->       0.421
                              (HP)          ---->       0.564
    -->  FRICTION POWER, ALL MAIN BEARINGS
                              (KW)          ---->       0.458
                              (HP)          ---->       0.615
    -->  FRICTION POWER, ALL ROTOR BEARINGS
                              (KW)          ---->       1.588
                              (HP)          ---->       2.128
    -->  FRICTION POWER FOR ANCILLARY COMPONENTS
                              (KW)          ---->      10.787
                              (HP)          ---->      14.460
    -->  FRICTION POWER FOR ALL SEALS AND BEARINGS
                              (KW)          ---->       5.548
                              (HP)          ---->       7.437
```

```
-->  TOTAL FRICTION POWER
                           (KW)           ---->     16.335
                           (HP)           ---->     21.897


>>>>> HEAT TRANSFER


-->  MAXIMUM TROCHOID HOUSING SURFACE TEMPERATURE
                           (K)            ---->      450.0
                           (DEG F)        ---->      350.3
     MAX SURFACE TEMP OCCURS NEAR    0.00 DEG
-->  AVERAGE ROTOR SURFACE TEMPERATURE
                           (K)            ---->      500.0
                           (DEG F)        ---->      440.3
-->  TEMPERATURE DROP IN THE EXHAUST MANFOLD
                           (K)            ---->        3.9
                           (DEG F)        ---->        7.1
-->  (HEAT TRANSFER PER CYCLE)/(MASS OF FUEL TIMES LHV)
                           (%)            ---->       16.2
-->  HEAT TRANSFER TO ROTOR FACE, ONE CYCLE
                           (KJ)           ---->     0.0659
                           (BTU)          ---->     0.0625
-->  HEAT TRANSFER TO SIDE HOUSING, ONE CYCLE
                           (KJ)           ---->     0.0439
                           (BTU)          ---->     0.0416
-->  HEAT TRANSFER TO TROCHOID HOUSING, ONE CYCLE
                           (KJ)           ---->     0.0781
                           (BTU)          ---->     0.0740


>>>>> CHAMBER PROPERTIES


-->  MAXIMUM CHAMBER PRESSURE
                           (KPA)          ---->     3963.5
                           (PSI)          ---->     574.86
                           (ATM)          ---->      39.12
     MAX PRESSURE OCCURS AT   22.00 DEG
-->  MAXIMUM CHAMBER TEMPERATURE
                           (K)            ---->     2112.6
                           (DEG F)        ---->     3343.0
     MAX TEMPERATURE OCCURS AT   29.98 DEG
-->  MASS AVERAGED EXHAUST GAS TEMPERATURE
```

```
                    (K)              ---->     990.7
                    (DEG F)          ---->    1323.7
  -->  TIME AVERAGED EXHAUST GAS TEMPERATURE
                    (K)              ---->     830.0
                    (DEG F)          ---->    1034.3
  -->  TIME AVERAGED INTAKE MANIFOLD PRESSURE
                    (KPA)            ---->     101.3
                    (PSI)            ---->     14.70
                    (ATM)            ---->      1.00
  -->  TIME AVERAGED INTAKE MANIFOLD TEMPERATURE
                    (K)              ---->    310.00
                    (DEG F)          ---->     98.33
  -->  MAXIMUM INTAKE MANIFOLD PRESSURE
                    (KPA)            ---->     101.3
                    (PSI)            ---->     14.70
                    (ATM)            ---->      1.00
       MAX PRESSURE OCCURS AT -620.10 DEG
  -->  TIME AVERAGED EXHAUST MANIFOLD PRESSURE
                    (KPA)            ---->      96.2
                    (PSI)            ---->     13.96
                    (ATM)            ---->      0.95
  -->  TIME AVERAGED EXHAUST MANIFOLD TEMPERATURE
                    (K)              ---->    899.84
                    (DEG F)          ---->   1160.04


>>>>> MEAN EFFECTIVE PRESSURE AND POWER


  -->  GROSS INDICATED MEAN EFFECTIVE PRESSURE (IMEP)
                    (KPA)            ---->     760.9
                    (PSI)            ---->    110.37
                    (ATM)            ---->      7.51
  -->  PUMPING MEAN EFFECTIVE PRESSURE (PMEP)
                    (KPA)            ---->     -26.8
                    (PSI)            ---->     -3.88
                    (ATM)            ---->     -0.26
  -->  FRICTION MEAN EFFECTIVE PRESSURE (FMEP)
                    (KPA)            ---->     242.6
                    (PSI)            ---->     35.19
                    (ATM)            ---->      2.39
  -->  BRAKE MEAN EFFECTIVE PRESSURE (BMEP)
                    (KPA)            ---->     518.4
                    (PSI)            ---->     75.18
```

```
                       (ATM)           ---->        5.12
 -->  INDICATED POWER, ONE ROTOR (IHP)
                       (KW)            ---->       51.24
                       (HP)            ---->       68.69
 -->  FRICTION POWER, ONE ROTOR (FHP)
                       (KW)            ---->       16.34
                       (HP)            ---->       21.90
 -->  BRAKE POWER ONE ROTOR (BHP)
                       (KW)            ---->       34.90
                       (HP)            ---->       46.79


>>>>> EFFICIENCY AND FUEL CONSUMPTION


 -->  VOLUMETRIC EFFIC BASED ON INTAKE MANIFOLD PRESS
                       (%)             ---->        93.1
 -->  TRAPPING EFFICIENCY
                       (%)             ---->       100.5
 -->  GROSS INDICATED THERMAL EFFICIENCY
                       (%)             ---->        37.8
 -->  NET INDICATED THERMAL EFFICIENCY
                       (%)             ---->        36.4
 -->  GROSS INDICATED SPECIFIC FUEL CONSUMPTION (ISFC)
                       (G/IKW-HR)      ---->        215.
                       (LB/HP-HR)      ---->       0.353
 -->  BRAKE SPECIFIC FUEL CONSUMPTION (BSFC)
                       (G/IKW-HR)      ---->        315.
                       (LB/HP-HR)      ---->       0.519


>>>>> COMBUSTION


 -->  IGNITION DELAY (0 - 10%)
                       (CRANK ANGLE)   ---->       10.00
                       (MS)            ---->        0.24
 -->  BURN DURATION (10 - 90%)
                       (CRANK ANGLE)   ---->       25.99
                       (MS)            ---->        0.62


>>>>> MASS FLOW
```

```
-->  MASS IN CYLINDER AT TIME INTAKE PORT OPENS
                            (G)            ---->      0.093
                            (LBM)          ---->    0.00021
-->  MASS IN CYLINDER AT TIME INTAKE PORT CLOSES
                            (G)            ---->      0.676
                            (LBM)          ---->    0.00149
-->  MASS THROUGH THE INTAKE PORT (ONE CHAMBER)
                            (G/CYCLE)      ---->      0.669
                            (LBM/CYCLE)    ---->    0.00148
-->  MASS THROUGH THE EXHAUST PORT (ONE CHAMBER)
                            (G/CYCLE)      ---->      0.695
                            (LBM/CYCLE)    ---->    0.00153
-->  MASS OF FUEL INJECTED (ONE CHAMBER)
                            (G/CYCLE)      ---->      0.026
                            (LBM/CYCLE)    ---->    0.00006
-->  MASS LEAKED TO THE LEAD CREVICE (ONE CHAMBER)
                            (G/CYCLE)      ---->      0.000
                            (LBM/CYCLE)    ---->    0.00000
-->  MASS LEAKED TO THE LAG CREVICE (ONE CHAMBER)
                            (G/CYCLE)      ---->      0.000
                            (LBM/CYCLE)    ---->    0.00000
-->  TOTAL AIR TO ALL ROTORS FOR 1 CYCLE
                            (G/CYCLE)      ---->    2.00797
                            (LBM/CYCLE)    ---->    0.00443
-->  TOTAL AIR MASS FLOW RATE (TO ALL ROTORS)
                            (G/SEC)        ---->      78.09
                            (LBM/HR)       ---->      619.7
-->  TOTAL FUEL MASS FLOW RATE (TO ALL ROTORS)
                            (G/SEC)        ---->      3.057
                            (LBM/HR)       ---->       24.3
-->  RESIDUAL FRACTION                     ---->      0.022


>>>>> WORK, HEAT TRANSFER AND POWER


-->  HEAT TRANS TO STRUCTURE DURING COMBUST. AND EXPAN.
                            (KJ/CYCLE)     ---->      0.177
                            (BTU/CYCLE)    ---->      0.167
-->  INDICATED SHAFT WORK DURING COMBUST. AND EXPANS.
                            (KJ/CYCLE)     ---->      0.439
                            (BTU/CYCLE)    ---->      0.416
-->  HEAT TRANSFER TO STRUCTURE FOR ONE CHAMBER
```

```
                     (KJ/CYCLE)     ---->      0.188
                     (BTU/CYCLE)    ---->      0.178
-->  INDICATED SHAFT WORK FOR ONE CHAMBER
                     (KJ/CYCLE)     ---->      0.424
                     (BTU/CYCLE)    ---->      0.402
-->  INDICATED POWER (INCLUDING ALL ROTORS)
                     (KW)           ---->     49.435
                     (HP)           ---->     66.268
```

Table IV-5: Sample Input File RCEMAP.INP, Case 2

```
&RUNRCE
   NROTOR  = 1
   IFUELT  = 1
   PIM     = 1.0
   PEM     = 0.95
   NALT    = 1
   ALTL    = 0.
   ALTH    = 0.
   NRPM    = 4
   RPML    = 4000.
   RPMH    = 7000.
   NPHI    = 4
   PHIL    = 0.3
   PHIH    = 0.75
&END
```

Table IV-6: Sample Input File RCEMAP.OUT, Case 2

```
>>>>> RCE PERFORMANCE MAP ROUTINE OUTPUT


>>>>> ENGINE PERFORMANCE PARAMETERS FOR:

      INTAKE MANIFOLD PRESSURE     =      0.0000 ATM
      INTAKE MANIFOLD TEMPERATURE =     298.170 K
      EXHAUST MANIFOLD PRESSURE    =      0.9500 ATM


   >> AIR MASS FLOW RATE (LB/HR)

PHI\RPM      4000.00     5000.00     6000.00     7000.00
--------------------------------------------------------

 0.300        408.04      479.63      550.35      617.98
 0.450        399.40      475.89      548.64      619.13
 0.600        390.19      468.57      543.71      616.04
 0.750        380.07      459.34      536.04      610.36


   >> FUEL MASS FLOW RATE (LB/HR)

PHI\RPM      4000.00     5000.00     6000.00     7000.00
--------------------------------------------------------

 0.300          7.38        9.11       10.82       12.46
 0.450         10.68       13.35       15.93       18.38
 0.600         13.75       17.32       20.78       24.10
 0.750         16.56       21.03       25.38       29.58


   >> BRAKE POWER (BHP)

PHI\RPM      4000.00     5000.00     6000.00     7000.00
--------------------------------------------------------
```

0.300	13.31	15.46	16.78	16.95
0.450	21.19	26.13	30.02	32.65
0.600	27.67	35.06	41.40	46.45
0.750	32.66	42.28	50.96	58.30

>> HEAT TRANSFER TO COOLANT (% FUEL ENERGY)

PHI\RPM	4000.00	5000.00	6000.00	7000.00
0.300	16.95	15.60	14.74	14.17
0.450	18.52	16.83	15.66	14.86
0.600	20.18	18.19	16.80	15.79
0.750	22.28	20.02	18.44	17.24

>> FRICTION POWER (FHP)

PHI\RPM	4000.00	5000.00	6000.00	7000.00
0.300	8.47	12.02	16.36	21.54
0.450	8.50	12.11	16.47	21.67
0.600	8.55	12.18	16.57	21.79
0.750	8.60	12.25	16.65	21.89

>> MASS AVERAGED EXHAUST GAS TEMP (DEG R)

PHI\RPM	4000.00	5000.00	6000.00	7000.00
0.300	1127.85	1170.30	1201.80	1229.09
0.450	1386.21	1439.79	1482.96	1518.11
0.600	1618.77	1688.31	1742.64	1789.01
0.750	1830.27	1911.88	1976.08	2032.59

>> THERMAL EFFICIENCY

PHI\RPM	4000.00	5000.00	6000.00	7000.00
0.300	38.828	39.294	39.350	39.006
0.450	36.733	37.582	37.898	37.811
0.600	34.875	35.896	36.380	36.456
0.750	33.033	34.189	34.839	35.032

>> BRAKE SPECIFIC FUEL CONSUMPTION (LB/HP-HR)

PHI\RPM	4000.00	5000.00	6000.00	7000.00
0.300	0.554	0.589	0.645	0.735
0.450	0.504	0.511	0.531	0.563
0.600	0.497	0.494	0.502	0.519
0.750	0.507	0.498	0.498	0.508

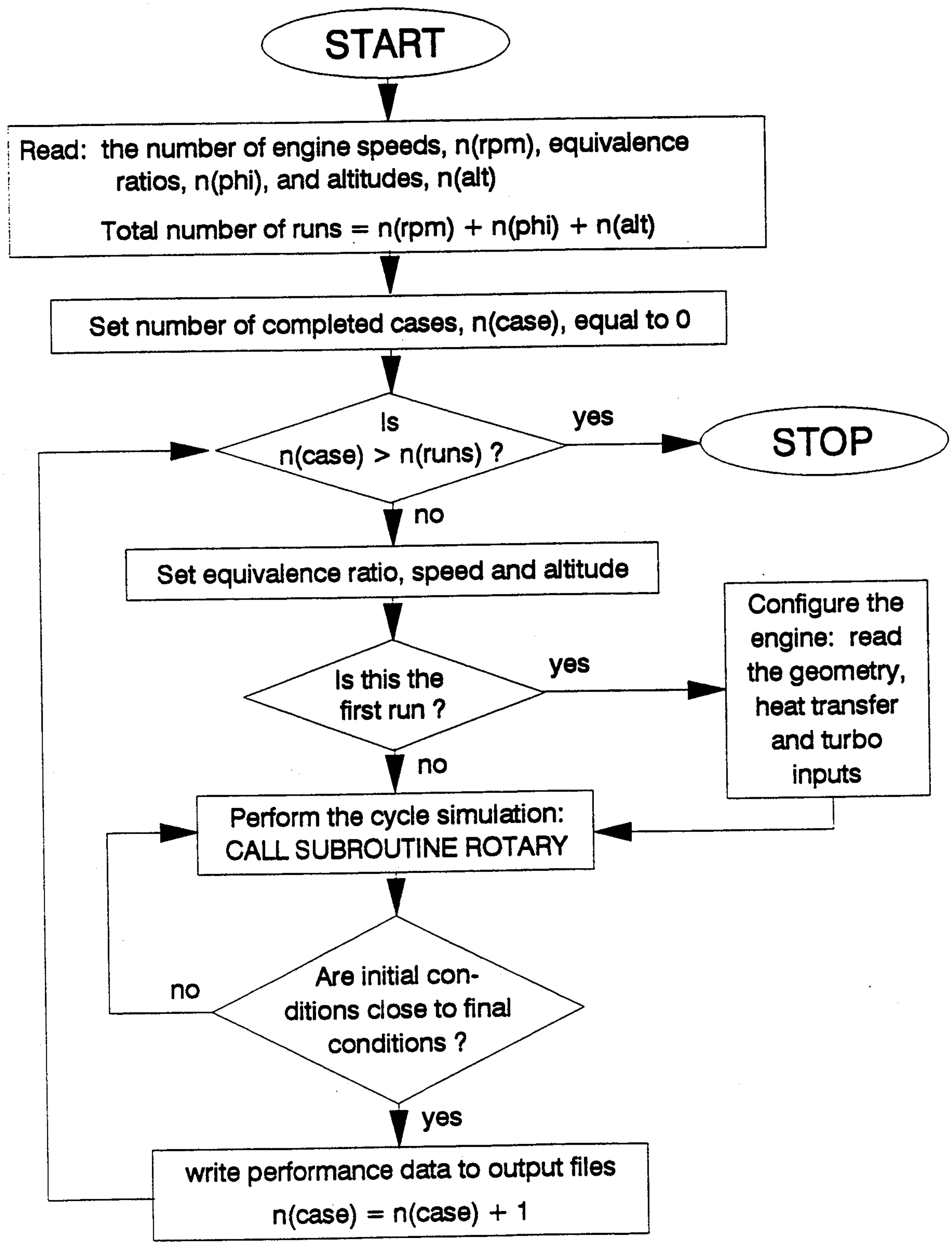


Figure IV-1: Flow Chart

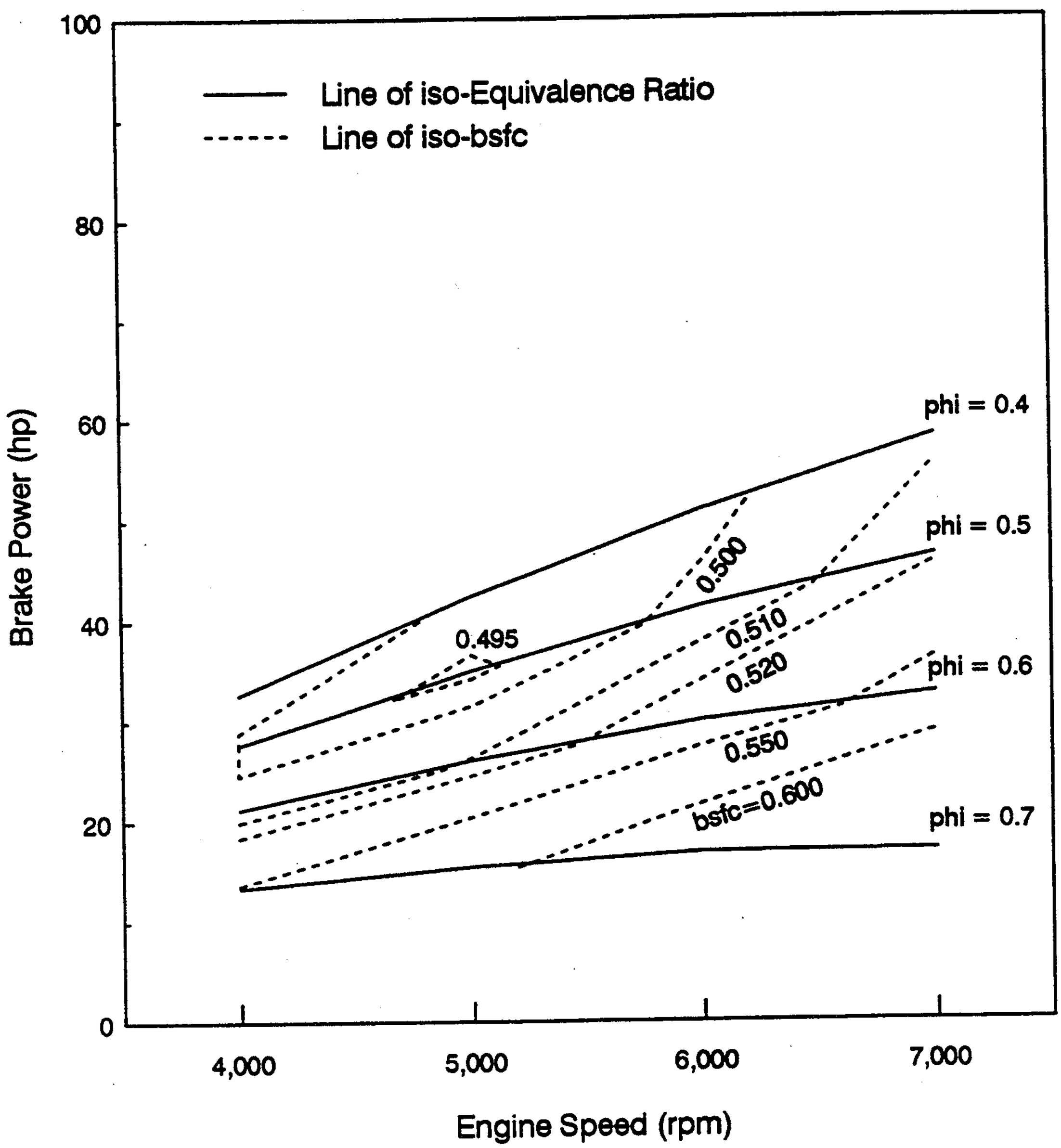


Figure IV-2: Engine Map for a Naturally Aspirated Rotary Combustion Engine

V INPUTS

To run RCEMAP, the user must provide between two and six input files, depending on the engine configuration. The files RCEMAP.INP and ROTARY.INP must <u>always</u> be provided. The files HHEAT.INP, RHEAT.INP and SHEAT.INP must be provided when the program calculates the trochoid housing, rotor face and sideplates temperatures internally. The user must provide the turbocharger data file TURB.DAT when a turbocharged engine is simulated.

All inputs except turbomachinery maps are provided to RCEMAP via namelists. An effort was made to give variables descriptive names and to be consistent. For example, all logical variables begin with the letter "L". All integer inputs begin with "I", "J", "K", "M", "N" and "O". All other variables are single-precision, real variables. There are six input files and up to ten output files generated by RCEMAP. The input files and their contents are described in detail below. The files are divided into three groups: geometry and operating condition inputs, heat transfer inputs and turbomachinery inputs.

V-A Engine Geometry and Operating Conditions

Two files contain engine operating condition and geometry inputs: RCEMAP.INP and ROTARY.INP. (All the input files should have the extension ".INP"). "Driver" file RCEMAP.INP specifies the number of operating conditions (load, speed and altitude) for which RCEMAP is run and provides estimates of intake and exhaust manifold pressures. File ROTARY.INP contains engine geometry, additional operating conditions and program-flow information such as the maximum allowable number of cycles. There are variables in ROTARY.INP which dictate whether heat transfer files HHEAT.INP, SHEAT.INP and RHEAT.INP and turbomachinery map file TURB.DAT are needed. Further information on heat transfer inputs and turbomachinery inputs is given below.

Following are descriptions of the variables in the geometry and operating condition input files, including comprehensive tables listing the files' variables, their FORTRAN variable type, descriptions and typical values.

<u>Input File RCEMAP.INP</u>

RCEMAP.INP contains one namelist, NLRCE. This input file was added to the original version of RCEMAP to facilitate multiple runs. Because initial conditions may not be too different when the engine is modeled at various operating conditions, the program runs faster when running back-to-back cases. The variables in RCEMAP.INP, their FORTRAN variable type and brief descriptions are found in Table V-1. Typical values for NLRCE's variables and the corresponding units are found in Table V-2.

The variables beginning with "N" determine the number of operating conditions for which RCEMAP runs. NALT is the number of altitudes, NRPM is the number of engine speeds and NPHI is the number of equivalence ratios. The total number of operating conditions is consequently NALT×NRPM×NPHI. To run only one case, set NALT, NRPM and NPHI all equal to one and set ALTL, RPML and PHIL equal to the desired values of altitude, engine speed and equivalence ratio, respectively.

Input File **ROTARY.INP**

Input file **ROTARY.INP** consists of the namelists described in Table V-3. There are up to 22 namelists which should be listed in input file **ROTARY.INP** in the same order as in Table V-3. The namelists in **ROTARY.INP** provide the engine geometry, heat transfer and combustion parameters, friction and losses parameters and mathematical constants used in the solution. Namelists **HPROF**, **SPROF** and **RPROF** need only be included when variables **IHTPRO**, **ISTPRO** or **IRTPRO** of namelist **NLHEAT** equal 2. Heat transfer inputs are described in greater detail below. Descriptions of the variables in the namelists of input file **ROTARY.INP** are found in Tables V-4 – V-42.

V-B Heat Transfer Inputs

Heat transfer rates to the rotor face, the trochoid housing and the side housings are calculated in one of three ways, depending on the values given to the variables **IRTPRO**, **IHTPRO** and **ISTPRO** in namelist **NLHEAT** in input file **ROTARY.INP**. The variable **IHTPRO** specifies how the trochoid housing surface temperature is calculated (surface temperature refers to the temperature on the hot gas/combustion chamber side of the housing material). **IRTPRO** specifies how the rotor face surface temperature is calculated and **ISTPRO** specifies how the side housing surface temperature is calculated. Heat transfer input files **HHEAT.INP**, **SHEAT.INP**, and **RHEAT.INP** contain thermal properties and coolant boundary conditions for the trochoid housing, the side housings and the rotor, respectively. File **HHEAT.INP** is used only when variable **IHTPRO** of input file **ROTARY.INP** is equal to 3. Likewise, file **SHEAT.INP** is used only when **ISTPRO** equals 3 and **RHEAT.INP** is used only when **IRTPRO** equals 3.

Trochoid Housing Heat Transfer

IHTPRO can take on the values 1, 2 or 3. For **IHTPRO** = 1, the trochoid housing temperature is constant through the cycle and is set equal to the value **THOUSI** in namelist **NLHEAT** in input file **ROTARY.INP**. Keeping the trochoid housing temperature constant during the cycle is the easiest method of approximating wall temperature. However, that method is least accurate because there are hot spots and cool spots on the housing. Wall temperatures influence performance parameters such as volumetric efficiency and heat rejection rate.

For **IHTPRO** = 2, the housing temperature profile is read from namelist **HPROF** in input file **ROTARY.INP**. Namelist **HPROF** contains the variable **THSEG(30)**. The trochoid housing is divided into 30 segments, each with a "duration" of 36 crank angle degrees. The surface temperature at the midpoint of each of those segments is specified in **HPROF** as **THSEG(I)**. Segment number 1 is the segment at the start of the cycle (from the beginning of intake, to 36 degrees after the beginning of intake). Designating the beginning of intake as θ_{ipo}, the crank angles for which the segment temperatures are specified are $(\theta_{ipo}+18^\circ)$, $(\theta_{ipo}+18^\circ+1\times36^\circ)$, $(\theta_{ipo}+18^\circ+2\times36^\circ)$, $\ldots$ $(\theta_{ipo}+18^\circ+29\times36^\circ)$.

For **IHTPRO** = 3, the housing temperature profile is calculated internally, assuming steady state conduction/convection and using crank angle averaged temperatures and heat transfer coefficients (see the heat transfer portion of the formulation section of this report for detailed description of heat transfer calculations). Temperature is calculated at the 30 housing segment midpoint crank angles (the midpoint crank angles are described in the IHTPRO = 2 section above).

When IHTPRO = 3, the thickness, thermal properties and coolant side boundary conditions of the trochoid housing must be input in input file HHEAT.INP. The file HHEAT.INP consists of three namelists: HOUSI1, HOUSI2 and HOUSI3. A sample of file HHEAT.INP is presented in Table V-43. The namelist HOUSI1 contains initial guesses for housing temperatures and coolant-side heat transfer coefficients as well as bulk coolant temperature. The variables in namelist HOUSI1 are listed and described in Table V-44 and V-45. Namelist HOUSI2 contains thermal property data for the trochoid housing structure. The trochoid housing can be made of up to three materials, each with its own thickness and thermal conductivity. The variables input in namelist HOUSI2 are listed and described in Table V-46 and V-47. Finally, namelist HOUSI3 contains coolant data used for calculation of the coolant heat transfer coefficient. The variables input in namelist HOUSI3 are listed and described in Table V-48 and V-49. As described in the formulation section of this user's guide, the coolant may undergo nucleate boiling at the trochoid housing hot-spots. See Chapter V, section D (page 22) for details on the coolant side heat transfer formulation.

Side Housing Heat Transfer

ISTPRO is the equivalent of IHTPRO for calculation of the side housing surface temperatures. ISTPRO can also equal 1, 2 or 3. For each of these values of ISTPRO, the side housing surface temperature is calculated in the same way the trochoid housing surface temperature is calculated when IHTPRO is given the same value. The side housings are also divided into 30 segments for ISTPRO = 2 or 3.

For ISTPRO = 2, the side housing temperature profile is input in namelist SPROF in input file ROTARY.INP. Namelist SPROF consists of the variable TSSEG(30), which is the midpoint side housing temperatures for the 30 side housing segments.

For ISTPRO = 3, side housing thickness, thermal properties and coolant side boundary conditions are input in input file SHEAT.INP. An example of the file SHEAT.INP is found in Table V-50. The file SHEAT.INP consists of two namelists: SIDE1 and SIDE2. Namelist SIDE1 contains guesses at segment side housing surface temperature, coolant side coolant temperature and coolant side heat transfer coefficient. Note that this is slightly different from the inputs in HHEAT.INP. Here the actual coolant side temperature and heat transfer coefficient are input (not calculated internally). The variables input in namelist SIDE1 are listed and described in Table V-51 and V-52.

Namelist SIDE2 contains thermal property data for the side housing structure. The side housing can be made of up to three materials, each with its own thickness and thermal conductivity. The variables input in namelist SIDE2 are listed and described in Tables V-53 and V-54.

Rotor Face Heat Transfer

For IRTPRO = 1, the rotor face surface temperature is input as variable TROTI in namelist NLHEAT of input file ROTARY.INP. The value of rotor face surface temperature is not varied during program execution when IRTPRO = 1.

For IRTPRO = 2, the user inputs a rotor surface temperature history via namelist RPROF in input file ROTARY.INP. Just as for the trochoid housing and the side housings, the cycle is broken into 30 segments and an average rotor surface temperature is input for the midpoint crank angle of each segment. The segment midpoints are the same as described above for IHTPRO = 2. The user input rotor face temperature history is not changed during execution when IRTPRO = 2.

When IRTPRO = 3, an energy balance is performed on the rotor face after each cycle. This enables calculation of the next cycle's rotor face temperature. Thermal properties of the rotor material, coolant side boundary conditions and thicknesses are specified in input file RHEAT.INP. When IRTPRO = 3, the rotor face temperature is not varied during the cycle, but is changed between cycles.

RHEAT.INP consists of two namelists: ROTIN1 and ROTIN2. A sample of input file RHEAT.INP is presented in Table V-55. Namelist ROTIN1 contains guess at rotor face surface temperature and coolant-side coolant temperature and heat transfer coefficient. Note that neither the rotor face temperature nor the coolant temperature or heat transfer coefficient varies during the cycle. Coolant side temperature and heat transfer coefficient are input, not calculated. The variables input in namelist ROTIN1 are listed and described in Tables V-56 and V-57. Note also that these variables are single-valued (not dimensioned).

ROTIN2 contains thermal property data for the rotor structure. The rotor housing can be made of up to three materials, each with its own thickness and thermal conductivity. The variables input in namelist ROTIN2 are listed and described in Tables V-58 and V-59.

This concludes the discussion of the heat transfer inputs in input file ROTARY.INP Namelists HPROF, SPROF and RPROF are summarized in Table V-42.

V-C Turbomachinery

If an engine is turbocharged, turbomachinery performance maps should be provided in input file TURB.DAT. TURB.DAT's data are in the same form as turbomachinery data for the NASA/Navy Engineering Program (NNEP) air-breathing engine modeling code. This is a result of an effort to integrate the NNEP code with a version of RCEMAP. For a conventionally turbocharged engine, the user must supply a set of compressor maps and a set of turbine maps. For a turbocharger with two stages of compression, two sets of compressor maps and one set of turbine maps should be provided.

Turbomachinery maps are placed in input file TURB.DAT. There must be at least five tables in TURB.DAT for a conventionally turbocharged engine: a compressor flow table; a compressor pressure ratio table; a compressor efficiency table; a turbine flow table and a turbine efficiency table. There must be at least eight tables when two-stage-compression turbocharging is used: two compressor flow tables; two compressor pressure ratio tables; two compressor efficiency tables; one turbine flow table and one turbine efficiency table.

Variables `ITABC1`, `ITABC2`, `ITABC3`, `ITABC4`, `ITABC5`, `ITABC6`, `ITABT1` and `ITABT2` (in namelist `NLOPCS` of input file `ROTARY.INP`) tell the program where (within the file `TURB.DAT`) the necessary turbomachinery tables are located. They refer to the position of the tables within `TURB.DAT`. There is room for confusion over what is meant by the table number. Table number is <u>not</u> the number found in the table title card. The table number tells which table inside file `TURB.DAT` contains the table. The first table in `TURB.DAT` (i.e., at the top of `TURB.DAT`) is table number 1. The second is table number 2, etc. Note that the table numbers on the title cards are not used in `RCEMAP`, but may be useful for the user to keep track of his/her turbomachinery data.

<u>Compressor Maps</u>

Figure V-1 shows a typical turbocharger compressor map. Before this map is discussed, the terms corrected speed and corrected flow as used below are explained. Turbomachinery data are often presented in terms of corrected speed and corrected flow. When corrected quantities are employed, maps can be used for a range of turbomachine inlet conditions. Normalized compressor inlet temperature, Θ, is defined as actual compressor inlet temperature, $T_{1,a}$, divided by compressor inlet temperature at which data were collected, $T_{1,s}$:

$$\Theta = \frac{T_{1,a}}{T_{1,s}} \tag{50}$$

Likewise, normalized inlet pressure, δ, is

$$\delta = \frac{P_{1,a}}{P_{1,s}} \tag{51}$$

Corrected speed, N^*, is defined as

$$N^* = \frac{N}{\sqrt{\Theta}} \tag{52}$$

where N is the turbomachine actual speed (rpm). Corrected flow, W^*, is defined:

$$W^* = \frac{W\sqrt{\Theta}}{\delta} \tag{53}$$

where W is flow rate through the machine.

Returning to the map in Figure V-1, the solid lines are lines of constant corrected speed and the dashed lines are interpolating lines ($\Re$ lines). These lines do not reflect performance; they were drawn by the user to make a grid from which data points are taken. Note how $\Re$ lines are numbered: the lowest value is assigned to the top line (near compressor surge) and the values increase down and to the right. The values of

$\Re$ are arbitrary, but must increase down and to the right, as described. The dotted lines in Figure V-1(b) are iso-efficiency lines.

For each compressor there should be three map tables in input file `TURB.DAT`: the first for corrected flow, the second for pressure ratio and the last for efficiency. Data points are read at the intersections of the $\Re$ lines and N^* lines. The first entry in compressor map tables corresponds to the intersection of the lowest value $\Re$ line and lowest value speed line.

A sample corrected flow table is found in Table V-60. The first line includes a table reference number (in columns 2 – 4) (very important: this number is not the table number the variable `ITABC1` is equal to!) and a description of the table. The second line is not used (although it may be in the future). It should have the letters `ANGL` in columns 1 – 4, the number `1` in column 7 and the number `0.0` in columns 19 – 21. The third line gives the corrected speed line values, from lowest to highest. The letters `SPED` should be in columns 1 – 4. The number of speed lines should be placed in columns 6 and 7 (as an integer). Values for corrected speed are in columns 11 – 81 in the format 7F10. The units for corrected speed are krpm. If there are more than 7 values for corrected speed, they are entered beginning in column 11 with the format 7F10. The next card tells how many $\Re$ lines there are and what their values are. The first column should have `R` in it. The number of $\Re$ lines should be placed in columns 6 and 7 and the values for $\Re$ should follow in the format 7F10., beginning in column 11. Subsequent cards provide corrected flow data corresponding to the appropriate $\Re$. The first four columns should read `FLOW`. The number of flow values should be in columns 6 and 7 (this should be the same as the number of $\Re$ lines. Flow data begin in column 11 and have the format 7F10. If extra rows of data are needed for a given speed, use the format 10X,7F10. After all the mass flow data are entered, the last line of the table should have the letters `EOT` in the first three columns.

Table V-61 is a sample compressor pressure ratio table. The compressor pressure ratio table is nearly identical to the flow table, except `FLOW` cards are replaced with `PR` cards. The format of the `PR` card is the same as that of `FLOW` cards.

Table V-62 is a sample compressor efficiency table. Once again, the efficiency table is nearly identical to the flow and pressure ratio tables. For the efficiency table, `FLOW` cards are replace with `EFF` cards.

Turbine Maps

Figure V-2 shows a typical turbocharger turbine map. The solid lines are "speed" lines; they give values of corrected flow as a function of pressure ratio for various values of corrected speed. The dashed lines are efficiency lines for various corrected speeds.

Turbocharger turbine data are found in two tables in input file `TURB.DAT`. The first table contains flow data and the second efficiency data.

Table V-63 is a sample turbocharger turbine flow rate map. Map entries are similar to those for compressor flow rate maps. The first line is a title card. Columns 2 – 5 are a map reference number and columns 7 – 72 contain the map title. The second line is currently not used (though it will be if variable area turbine is used). It should have the letters `ANGL` in the first four columns, the number 1 in column 6 and the number 0.0 in columns 19 – 21. The third card gives corrected speed values in krpm. The first four columns should read `SPED`. The number of speed lines is entered in columns 6 and 7, and values for corrected speed are entered beginning in column 11 and using the format 7F10. Beginning with the fourth line, pressure ratio cards alternate with corrected flow cards. Pressure ratio cards have the letters `PR` in columns 1 –2, the number of pressure ratio values in columns 6 – 7 and pressure ratio values in columns 11 – 81. Pressure ratios have the format 7F10. Corrected flow cards begin with `FLOW` in the first four columns, followed by the number of flow values in columns 6 and 7 and the flow values in columns 11 – 81.

The turbine efficiency map is nearly the same as the corrected flow map, except the `FLOW` rows are replaced by `EFF` rows. Table V-64 is a sample turbine efficiency map.

Table V-1: Namelist RUNRCE, file RCEMAP.INP: Variables' Descriptions

Variable	Type	Description
NROTOR	I*	Number of rotors
IFUELT	I	Fuel type: IFULET $= 1 \rightarrow$ fuel is iso-octane IFULET $= 2 \rightarrow$ fuel is propane IFULET $= 3 \rightarrow$ fuel is diesel
PIM	R	Intake manifold pressure estimate (atm)
PEM	R	Exhaust manifold pressure estimate (atm)
NALT**	I	Number of runs over the specified altitude range
ALTL	R	Lowest altitude in the altitude range (ft)
ALTH	R	Highest altitude in the altitude range (ft)
NRPM†	I	Number of runs over the specified engine speed range
RPML	R	Lowest speed in the engine speed range (rpm)
RPMH	R	Highest speed in the engine speed range (rpm)
NPHI‡	I	Number of runs over the specified equivalence ratio range
PHIL	R	Lowest equivalence ratio in the engine equivalence ratio range
PHIH	R	Highest equivalence ratio in the engine equivalence ratio range

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision.

** e.g., if NALT equals 3, ALTL equals 0 ft and ALTH equals 10,000 ft, RCEMAP is run at sea level, 5,000 ft and 10,000 ft for each engine speed and equivalence ratio.

† e.g., if NRPM is 3, RPML is 4000 rpm and RPMH is 8000 rpm, RCEMAP is run at 4000 rpm, 6000 rpm and 8000 rpm for each altitude and equivalence ratio.

‡ e.g., if NPHI equals 3, PHIL equals 0.4 and PHIH equals 0.8, RCEMAP is run at equivalence ratios 0.4, 0.6 and 0.8 for each altitude and engine speed.

Table V-2: Namelist RUNRCE, file RCEMAP.INP: Variables' Values and Units

Variable	Units	Typical Values
NROTOR		1 ≤ NROTOR ≤ 4
IFUELT		1 ≤ IFUELT ≤ 3
PIM	atm	Usually > 1 atm and PIM > PEM
PEM	atm	Ambient pressure < PEM < PIM
NALT		1 ≤ NALT ≤ 17
ALTL	ft	0 ≤ ALTL ≤ 65,000 ft and ALTL ≤ ALTH
ALTH	ft	0 ≤ ALTH ≤ 65,000 ft and ALTH ≥ ALTL
NRPM		1 ≤ NRPM ≤ 10
RPML	rpm	1500 ≤ RPML ≤ 15,000 and RPML ≤ RPMH
RPMH	rpm	1500 ≤ RPMH ≤ 15,000 and RPMH ≥ RPML
NPHI		1 ≤ NPHI ≤ 10
PHIL		0.3 ≤ PHIL ≤ 0.85 and PHIL ≤ PHIH
PHIH		0.3 ≤ PHIH ≤ 0.85 and PHIH ≥ PHIL

Table V-3: Namelists in Input File ROTARY.INP

NAMELIST	DESCRIPTION
NLCASE	Case number, date of run and allowed number of cycles
NLOPCS	Engine operating conditions and configuration
NLGEOM	Geometry
NLHREL	Combustion heat release rate constants
NLPORT	Port geometry, timings and discharge coefficients
NLHEAT	Coolant heat rejection constants and temperatures
NLIMAN	Intake manifold geometry
NLEMAN	Exhaust manifold geometry
NLWRIT	Output specifications
NLCONV	Convergence criteria
NLAPEX	Apex seal geometry and spring force
NLSIDE	Side seal geometry and spring force
NLOILS	Oil seal geometry and spring force
EXHFL	Exhaust pipe properties (for calculating temperature drop in the exhaust manifold)
ROTORB	Rotor bearing geometry
MAINB	Main bearing geometry
ACOOL*	Aftercooler geometry and operation
ICOOL**	Intercooler geometry and operation
NLWG*	Wastegate cracking pressure and geometry
HPROF	Trochoid housing wall temperature profile
SPROF	Side housing wall temperature profile
RPROF	Rotor face surface temperature profile

* Only used for single-stage and two-stage compression turbocharged engines.

** Only used for two-stage compression turbocharged engines.

Table V-4: Namelist NLCASE, file ROTARY.INP: Variables' Descriptions

Variable	Type	Description
ICASE	I*	Case number
IDAY	I	Day (numerical)
IMONTH	I	Month (numerical)
IYEAR	I	Year
MAXITS	I	Maximum number of cycles allowable. The code runs until it converges (final conditions are close to initial conditions) or until MAXITS is reached.

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision.

Table V-5: Namelist NLCASE, file ROTARY.INP: Variables' Values and Units

Variable	Units	Typical Values
ICASE		$1 \leq$ ICASE ≤ 999
IDAY		$1 \leq$ IDAY ≤ 31
IMONTH		$1 \leq$ IMONTH ≤ 12
IYEAR		$1 \leq$ IYEAR ≤ 9999
MAXITS		$6 \leq$ MAXITS ≤ 20. It is possible to make MAXITS lower than 6 or greater than 20, but this may lead to inaccuracy or wasted computer time.

Table V-6: Namelist NLOPCS, file ROTARY.INP: Variables' Descriptions

Variable	Type	Description
LFIRE	L*	LFIRE = .TRUE. → engine is fired LFIRE = .FALSE. → engine is motored
LTCHAR	L	LTCHAR = .TRUE. → engine is turbocharged LTCHAR = .FALSE. → engine is naturally aspirated or supercharged
L2C	L	L2C = .TRUE. → two-stage compression turbocharger L2C = .FALSE. → conventional turbocharger
EGR	R	Exhaust gas recirculation fraction (%)
TEGR	R	Exhaust gas recirculation temperature (K)
ANCIL1	R	Constant, C_{A1}, in the expression:

$$fmep_a = C_{A1} + C_{A2}\left(\frac{N}{1000}\right) + C_{A3}\left(\frac{N}{1000}\right)^2 \quad (51)$$

Variable	Type	Description
		for calculation of friction mep associated with ancillary losses. See section II-E for further description.
ANCIL2	R	Constant C_{A2} in the above expression.
ANCIL3	R	Constant C_{A3} in the above expression.
ITABC1**	I	Table number for compressor flow rate. Corresponds to the second stage of compression for a two-stage compression turbocharger.
ITABC2**	I	Table number for compressor pressure ratio. Corresponds to the second stage of compression for a two stage compression turbocharger.
ITABC3**	I	Table number for compressor efficiency. Corresponds to the second stage of compression for a two stage compression turbocharger.
ITABC4**	I	Table number for compressor flow rate for the low pressure compressor in a two-stage-compression turbocharger.

Table V-6: (Continued)

Variable	Type	Description
ITABC5**	I	Table number for compressor pressure ratio for the low pressure compressor in a two-stage-compression turbocharger.
ITABC6**	I	Table number for compressor efficiency for the low pressure compressor in a two-stage-compression turbocharger.
ITABT1**	I	Table number for turbocharger turbine flow rate
ITABT2**	I	Table number for turbocharger turbine efficiency.
RCORR	R(6)	Temperature and pressure corrections RCORR(1) → High pressure compressor temperature correction RCORR(2) → High pressure compressor pressure correction RCORR(3) → Turbine temperature correction RCORR(4) → Turbine pressure correction RCORR(5) → Low pressure compressor temperature correction RCORR(6) → Low pressure compressor pressure correction

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision. Numbers in parentheses denote the dimension (number of values) for the variable.

** Further explanation of turbomachinery inputs is found in section V-C.

Table V-7: Namelist NLOPCS, file ROTARY.INP: Variables' Values and Units

Variable	Units	Typical Values
LFIRE		.TRUE. or .FALSE.
LTCHAR		.TRUE. or .FALSE.
L2C		.TRUE. or .FALSE.
EGR	%	0. ≤ EGR ≤ 100.
TEGR	K	Ambient temperature ≤ TEGR ≤ 2000.
ANCIL1		A typical value for ANCIL1 is 0.3680. ANCIL1, ANCIL2 and ANCIL3 should be set by fitting the anillary losses expression to engine data.
ANCIL2		A typical value for ANCIL2 is 0.1319
ANCIL3		A typical value for ANCIL3 is 0.0059
ITABC1		1 ≤ ITABC1 ≤ 99
ITABC2		1 ≤ ITABC2 ≤ 99
ITABC3		1 ≤ ITABC3 ≤ 99
ITABC4		1 ≤ ITABC4 ≤ 99
ITABC5		1 ≤ ITABC5 ≤ 99
ITABC6		1 ≤ ITABC6 ≤ 99
ITABT1		1 ≤ ITABT1 ≤ 99
ITABT2		1 ≤ ITABT2 ≤ 99
RCORR(1)	°R	Typical value: 520.
RCORR(2)	psi	Typical value: 14.69
RCORR(3)	°R	Typical value: 520.
RCORR(4)	psi	Typical value: 14.69
RCORR(5)	°R	Typical value: 520.
RCORR(6)	psi	Typical value: 14.69

Table V-8: Namelist NLGEOM, file ROTARY.INP: Variables' Descriptions

Variable	Type	Description
ECCEN	R*	Eccentricity (cm)
ROTRAD	R	Rotor radius (cm)
DEPTH	R	Chamber depth (cm)
VFLANK	R	Rotor pocket volume (cc)
SZOVER	R	Trochoid housing over-size (cm)
CLRNCE	R	Apex seal tip clearance (cm)
AREALK	R	Sum of leakage areas for one chamber (cm^2)
CREVOL	R	Sum of crevice volumes for one chamber (cc)

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision. Numbers in parentheses denote the dimension (number of values) for the variable.

Table V-9: Namelist NLGEOM, file ROTARY.INP: Variables' Values and Units

Variable	Units	Typical Values
ECCEN	cm	Typical value: 1.5
ROTRAD	cm	Typical value: 10.6
DEPTH	cm	Typical value: 7.
VFLANK	cc	Typical value: 40.
SZOVER	cm	Typical value: 0.08
CLRNCE	cm	Typical value: 0.064
AREALK	cm^2	$0 \geq$ AREALK. Large values of AREALK (e.g., ≥ 0.025 for a 40 in^3 engine) hinder convergence.
CREVOL	cc	CREVOL ≥ 0. Typical value: 0.5

Table V-10: Namelist `NLHREL`, file `ROTARY.INP`: Variables' Descriptions

Variable	Type	Description
TSPARK	R*	Crank angle at which combustion commences. That is, θ_s in the expression

$$\frac{dQ_c}{d\theta} = \begin{cases} \left(\frac{dQ_c}{d\theta}\right)_{max} \left(\frac{\theta-\theta_s}{\theta_m-\theta_s}\right) & \text{for } \theta_s \leq \theta \leq \theta_m \\ \left(\frac{dQ_c}{d\theta}\right)_{max} e^{\frac{-(\theta-\theta_m)}{\tau}} & \text{for } \theta > \theta_m \end{cases} \tag{61}$$

Variable	Type	Description
XBZERO	R	Mass fraction of the fuel burnt before crank angle θ_s
XBSTOP	R	Mass fraction of the fuel burnt during the combustion process (maximum = 1.0)
TMAX	R	Angle at which the maximum combustion heat release rate occurs. That is, θ_m in equation 61.
DQDTMX	R	Normalized maximum combustion heat release rate. That is, $\frac{\left(\frac{dQ_c}{d\theta}\right)_{max}}{m_f \times LHV}$, where m_f is the mass of fuel injected per cycle and LHV is the fuel lower heating value.

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision. Numbers in parentheses denote the dimension (number of values) for the variable.

Table V-11: Namelist NLHREL, file ROTARY.INP: Variables' Values and Units

Variable	Units	Typical Values
TSPARK	deg	TSPARK $<$ 0. Typical value: -15.
XBZERO		0. $\leq$ XBZERO $\leq$ 0.1
XBSTOP		XBSTOP $\leq$ 1.
TMAX	deg	TMAX $>$ TSPARK
DQDTMX	deg^{-1}	DQDTMX, TMAX and TSPARK should be estimated from engine pressure data. A typical value for DQDTMX is 0.055. DQDTMX, TMAX and TSPARK are limited to values for which the decay constant, τ, in Equation 63 is positive.

$$\tau = \tfrac{1}{2}(\theta_m - \theta_s) - \frac{X_c \, m_{f,cycle} \times LHV}{\left(\frac{dQ_c}{d\theta}\right)_{max}} \tag{63}$$

Table V-12: Namelist `NLPORT`, file `ROTARY.INP`: Variables' Descriptions

Variable	Type	Description
`IPA`	R*	Intake port area
`EPA`	R	Exhaust port area
`CDIP`	R	Intake port discharge coefficient
`CDEP`	R	Exhaust port discharge coefficient
`TIPO`	R	Crank angle at which the intake port begins to open (deg before TC; should be negative)
`TIPC`	R	Crank angle at which the intake port is fully closed. (deg before TC; should be negative)
`TEPO`	R	Crank angle at which the exhaust port begins to open (deg after TC; should be positive)
`TEPC`	R	Crank angle at which the exhaust port is fully closed (deg after TC; should be positive)
`THIPO`	R	Crank angle increment for the intake port to open fully (see Figure III-1)
`THEPO`	R	Crank angle increment for the exhaust port to open fully (see Figure III-1)

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision. Numbers in parentheses denote the dimension (number of values) for the variable.

Table V-13: Namelist NLPORT, file ROTARY.INP: Variables' Values and Units

Variable	Units	Typical Values
IPA	cm^2	Typical value: 10. A large intake port may hinder convergence.
EPA	cm^2	Typical value: 10. A large exhaust port may hinder convergence.
CDIP		CDIP $\leq$ 1. Typical value: 0.6
CDEP		CDEP $\leq$ 1. Typical value: 0.5
TIPO	deg	Typical value: -550.
TIPC	deg	Typical value: -200.
TEPO	deg	Typical value: 199.
TEPC	deg	Typical value: 588.5
THIPO	deg	Typical value for peripheral port: 60.
THEPO	deg	Typical value: 40.

Table V-14: Namelist NLHEAT, file ROTARY.INP: Variables' Descriptions

Variable	Type	Description
IHTPRO	I*	Determines whether trochoid housing wall temperature is calculated or assigned. 1 → user-input, constant wall temperature 2 → user-input wall temperature profile 3 → Wall temperature calculated internally
ISTPRO	I	Determines whether side housing temperature is calculated or assigned. 1 → user-input, constant housing temperature 2 → user input housing temperature profile 3 → Housing temperature calculated internally.
IRTPRO	I	Determines whether rotor face temperature is calculated or assigned. 1 → user-input, constant, rotor face temperature 2 → user-input rotor face temperature profile 3 → Rotor face temperature calculated internally
THOUSI	R	For IHTPRO equal to 1, THOUSI is the trochoid housing temperature during the entire cycle. For IHTPRO equal to 3, THOUSI is a guess at housing temperature, used only in the first cycle. THOUSI is not used when IHTPRO equals 2.
TSIDI	R	For ISTPRO equal to 1, TSIDI is the side housing temperature during the entire cycle. For ISTPRO equal to 3, TSIDI is a guess at housing temperature, used only in the first cycle. TSIDI is not used when ISTPRO equals 2.
TROTI	R	For IRTPRO equal to 1, TROTI is the rotor face temperature during the entire cycle. For IRTPRO equal to 3, TROTI is a guess at rotor face temperature, used only in the first cycle. TROTI is not used when IRTPRO equals 2.
CONHT	R	Constant, α, in the hot-gas-side Nusselt number expression $N_u = \alpha\ R_e^a \quad (14)$
EXPHT	R	Constant, a, in equation 14.

Table V-14: (Continued)

Variable	Type	Description
`CON1`	R	Constant c_1 in the gas velocity expression

$$v_{firing} = c_1 v_{non-firing} + c_2 \left(\frac{V_c}{V_{ipc}}\right)\left(\frac{T_{ipc}}{P_{ipc}}\right)(P_c - P_{non-firing}) \tag{12}$$

Variable	Type	Description
`CON2`	R	Constant c_2 in Equation 12.
`CON3`	R	Not used. Must equal 0.
`ALFF`	R	Not used. Can be set to any value.
`PRNDTL`	R	Not used. Can be set to any value.
`LCOUET`	L	Not used. Must equal `.F.`).

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision. Numbers in parentheses denote the dimension (number of values) for the variable.

Table V-15: Namelist NLHEAT, file ROTARY.INP: Variables' Values and Units

Variable	Units	Typical Values
IHTPRO		1 ≤ IHTPRO ≤ 3
ISTPRO		1 ≤ ISTPRO ≤ 3
IRTPRO		1 ≤ IRTPRO ≤ 3
THOUSI	K	Typical value: 400 K
TSIDI	K	Typical value: 400 K
TROTI	K	Typical value: 500 K
CONHT		In the original Woscnhi formulation (ref 6), CONHT = 0.037
EXPHT		In the original Woschni formulation, EXPHT = 0.8
CON1		Should be close to 1. In original version of code, CON1 = 0.75.
CON2		Should be on the order of 1. In original version of the code, CON2 = 0.324. The authors have used values greater than 1.
CON3		Must equal 0.
ALFF		Any value (not used).
PRNDTL		Any value (not used).
LCOUET		Must equal .F.

Table V-16: Namelist NLIMAN, file ROTARY.INP: Variables' Descriptions

Variable	Type	Description
LPIM	L*	When LPIM is .TRUE., intake manifold pressure, temperature and mass vary during the cycle via the emptying and filling model described in section III-G. Otherwise, intake manifold pressure and temperature do not vary during the cycle.
VIM	R	Intake manifold volume (including aftercooler volume) (cc).
TIM	R	Intake manifold temperature (used only when LPIM = .FALSE. and there is no turbocharger).

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision. Numbers in parentheses denote the dimension (number of values) for the variable.

Table V-17: Namelist NLIMAN, file ROTARY.INP: Variables' Values and Units

Variable	Units	Typical Values
LPIM		.TRUE. or .FALSE.
VIM	cc	Typical value: 2500 for a 40 in^3 engine with an aftercooler
TIM	K	TIM $\geq$ ambient temperature. Typical value: 350.

Table V-18: Namelist NLEMAN, file ROTARY.INP: Variables' Descriptions

Variable	Type	Description
LPEM	L*	When LPEM is .TRUE., exhaust manifold pressure, temperature, mass and composition vary during the cycle via the emptying and filling model described in section III-G. Otherwise, exhaust manifold pressure, temperature and composition do not vary during the cycle.
VEM	R	Exhaust manifold volume (cc).
PEXH	R	Exhaust manifold pressure (atm) (used only when LPEM = .FALSE. and there is no turbocharger).

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision. Numbers in parentheses denote the dimension (number of values) for the variable.

Table V-19: Namelist NLIMAN, file ROTARY.INP: Variables' Values and Units

Variable	Units	Typical Values
LPEM		.TRUE. or .FALSE.
VEM	cc	Typical value: 500 for a 40 in^3 engine
PEXH	atm	PEXH $\geq$ ambient pressure. Typical value: 1.0

Table V-20: Namelist NLWRIT, file ROTARY.INP: Variables' Descriptions

Variable	Type	Description
LDEBUG	L(15)*	Output control variable. When LDEBUG(I) is .TRUE, data is output to unit I. A brief listing of the output units is provided below. A more detailed description is provided in the outputs section of this guide (section VI). Unit 1 → Comprehensive output: performance and P-V-T data (very long file) Unit 2 → Crank-angle-by-crank-angle P-V-T data Unit 3 → Performance data (short file) Unit 4 → Intake manifold properties Unit 5 → Heat transfer data Unit 6 → Engine mass and composition Unit 7 → Trochoid housing heat loss and temp Unit 8 → Crevice and leakage flows data Unit 9 → Seal and bearing friction Unit 10 → Side housing heat loss and temp Unit 11 → Not used Unit 12 → Not used Unit 13 → Not used Unit 14 → Not used Unit 15 → Not used
LBRIEF	L	Controls the amount of output to unit 3 (file RSHORT.OUT). When LBRIEF = .TRUE., only limited input data are echoed. When LBRIEF = .FALSE., input data are echoed.
LSI	L	Determines units of the outputs LSI = .TRUE. → outputs in SI units. LSI = .FALSE. → outputs in USCS units.
TPRINT	R	Crank-angle interval between outputs during intake, compression and exhaust
TPRINX	R	Crank-angle interval between outputs during combustion and expansion.

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision. Numbers in parentheses denote the dimension (number of values) for the variable.

Table V-21: Namelist NLWRIT, file ROTARY.INP: Variables' Values and Units

Variable	Units	Typical Values
LDEBUG		For non-debugging runs when only engine performance is desired, set
		LDEBUG = .F.,.F.,.T.,.F.,.F.,.F.,.F.,.F.,.F.,.F.,.F.,.F.,.F.,.F.,.F.
		For P-V-T as well as performance data, set
		LDEBUG = .T.,.T.,.T.,.F.,.F.,.F.,.F.,.F.,.F.,.F.,.F.,.F.,.F.,.F.,.F.
		Consult the outputs section of this guide if more information is needed
LBRIEF	deg	Either .TRUE or .FALSE.
LSI	deg	Either .TRUE or .FALSE.
TPRINT	deg	Typically, TPRINT = 10. If TPRINT is too small, output may be voluminous.
TPRINX	deg	Typically, TPRINX = 5. If TPRINX is too small, output may be voluminous.

Table V-22: Namelist `NLCONV`, file `ROTARY.INP`: Variables' Descriptions

Variable	Type	Description
TCONV	R*	Temperature convergence criterion**
PCONV	R	Pressure convergence criterion**
XMCONV	R	Chamber mass convergence criterion**
TRCONV	R	Rotor face temperature convergence criterion** Only used when IRTPRO = 3.
THCONV	R	Trochoid housing temperature convergence criterion** Only used when IHTPRO = 3.
PMCONV	R	Intake manifold pressure convergence criterion. Only used when LPIM = .T.
EMCONV	R	Exhaust manifold pressure convergence criterion. Only used when LPEM = .T.

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision. Numbers in parentheses denote the dimension (number of values) for the variable.

** Convergence tolerances give the allowable fraction of change in various properties from the beginning to the end of the cycle. For example, TCONV = 0.01 means the final gas temperature must be ± 1% of the initial gas temperature.

Table V-23: Namelist NLCONV, file ROTARY.INP: Variables' Values and Units

Variable	Units	Typical Values
TCONV		Typical value: 0.01*
PCONV		Typical value: 0.01*
XMCONV		Typical value: 0.01*
TRCONV		Typical value: 0.01*
THCONV		Typical value: 0.01*
PMCONV		Typical value: 0.01*
EMCONV		Typical value: 0.01*

* Typically, all convergence criteria are set to 0.01. Because turbocharged engine cases may convergence slowly, convergence criteria may be satisfied before the a converged solution is reached. Occasionally, the user should set the convergence criteria very low (e.g., 0.001) and allow the program to run to the maximum number of cycles. By doing this, the user sees whether the solutions truly are converging.

Table V-24: Namelist ACOOL, file ROTARY.INP: Variables' Descriptions

Variable	Type	Description
DPAC	R*	Aftercooler pressure drop (atm)
HAFTC	R	Gas-side heat transfer coefficient in the aftercooler (W/m^2-K)
TACIN	R	Liquid temperature as it enters the aftercooler (K)
AAFTC	R	Surface area of coolant tubes in the aftercooler (cm^2)

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision. Numbers in parentheses denote the dimension (number of values) for the variable.

Table V-25: Namelist ACOOL, file ROTARY.INP: Variables' Values and Units

Variable	Units	Typical Values
DPAC	atm	Typical value: 0.05.If DPAC is so large the average intake manifold pressure falls below the average exhaust manifold pressure, the code will probably not converge.
HAFTC	$\frac{W}{m^2 K}$	Typical value: 400. Should be estimated based on cross-flow liquid-air heat exchanger design.
TACIN	K	Typical value: 320 K.
AAFTC	m^2	Typical value: 0.4. Note: DPAC and AAFTC are not independent.

Table V-26: Namelist ICOOL, file ROTARY.INP: Variables' Descriptions

Variable	Type	Description
DPIC	R*	Intercooler pressure drop (atm)
HINTC	R	Gas-side heat transfer coefficient in the intercooler (W/m^2-K)
TICIN	R	Liquid temperature as it enters the intercooler (K)
AINTC	R	Surface area of coolant tubes in the intercooler (cm^2)

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision. Numbers in parentheses denote the dimension (number of values) for the variable.

Table V-27: Namelist ICOOL, file ROTARY.INP: Variables' Values and Units

Variable	Units	Typical Values
DPIC	atm	Typical value: 0.05. If DPIC is so large the average intake manifold pressure falls below the average exhaust manifold pressure, the code probably will not converge.
HINTC	$\frac{W}{m^2 K}$	Typical value: 400. Should be estimated based on cross-flow liquid-air heat exchanger design.
TICIN	K	Typical value: 320 K.
AINTC	m^2	Typical value: 0.4. Note: DPIC and AINTC are not independent.

Table V-28: Namelist NLAPEX, file ROTARY.INP: Variables' Descriptions

Variable	Type	Description
ABASE	R*	Apex seal base dimension (cm) (see Figure III-3)
AFRC1	R	Coefficient of sliding friction for friction between the apex seal tip and the trochoid housing
AFRC2	R	Coefficient of sliding friction for friction between the apex seal and the seal slot
AHEIG	R	Apex seal height (cm) (see Figure III-3)
AMASS	R	Apex seal mass (g)
ARAD	R	Apex seal tip radius of curvature (cm) (see Figure III-3)
FSPRI	R	Spring force on the apex seal base (N) (See Figure III-3)

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision. Numbers in parentheses denote the dimension (number of values) for the variable.

Table V-29: Namelist NLAPEX, file ROTARY.INP: Variables' Values and Units

Variable	Units	Typical Values
ABASE	cm	For a 40 in^3 engine, ABASE = 0.18
AFRC1		Typical value: 0.07
AFRC2		Typical value: 0.13
AHEIG	cm	For a 40 in^3 engine, AHEIG = 0.8
AMASS	g	Typical value: 30 g.
ARAD	cm	For a 40 in^3 engine, ARAD = 0.081
FSPRI	N	Typical value: 35.

Table V-30: Namelist NLSIDE, file ROTARY.INP: Variables' Descriptions

Variable	Type	Description
SIDEB	R*	Side seal base dimension (cm) (see Figure III-4)
SIDEH	R	Side seal height (cm) (see Figure III-4)
SIDECF	R	Coefficient of sliding friction between the side seal and side housing.
SIDEF	R	Spring force on the side seal base (N) (See Figure III-4)

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision. Numbers in parentheses denote the dimension (number of values) for the variable.

Table V-31: Namelist NLSIDE, file ROTARY.INP: Variables' Values and Units

Variable	Units	Typical Values
SIDEB	cm	For a 40 in^3 engine, SIDEB = 0.18
SIDEH	cm	For a 40 in^3 engine SIDEH = 0.24
SIDECF		Typical value: 0.06
SIDEF	N	Typical value: 70 N.

Table V-32: Namelist NLOILS, file ROTARY.INP: Variables' Descriptions

Variable	Type	Description
SOILB	R*	Oil seal base dimension (cm) (see Figure III-5)
SOILCF	R	Coefficient of sliding friction between the oil seal and side housing.
SOILF	R	Spring force on the oil seal base (N) (See Figure III-5)
SOILR	R	Oil seal radius (cm) (see Figure III-5)
SOILP	R	Crank case pressure (atm)

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision. Numbers in parentheses denote the dimension (number of values) for the variable.

Table V-33: Namelist NLOILS, file ROTARY.INP: Variables' Values and Units

Variable	Units	Typical Values
SOILB	cm	Typical value: 0.15
SOILCF		Typical value: 0.06
SOILF	N	Typical value: 22.
SOILR	cm	For a 40 in^3 engine, SOILR = 6.
SOILP	atm	SOILP $\geq$ ambient pressure. Typical value: 2 atm.

Table V-34: Namelist EXHFL, file ROTARY.INP: Variables' Descriptions

Variable	Type	Description
EPTHIK	R*	Exhaust pipe thickness (cm)
EXHPL	R	Exhaust pipe length (to turbine) (cm)
TPOUT	R	Temperature outside the exhaust pipe (K)
TCONP	R	Exhaust pipe thermal conductivity (W/m-K)
EXHPEM	R	Emissivity of the exhaust pipe exterior surface
FEXHP	R	Shape factor for exhaust pipe exterior

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision. Numbers in parentheses denote the dimension (number of values) for the variable.

Table V-35: Namelist EXHFL, file ROTARY.INP: Variables' Values and Units

Variable	Units	Typical Values
EPTHIK	cm	Typical value: EPTHIK = 0.25 cm
EXHPL	cm	For a 40 in^3 engine, EXHPL = 7.62 cm
TPOUT	cm	TPOUT $\geq$ ambient temperature. Typical value: 350
TCONP	$\frac{W}{m\,K}$	For an iron exhaust pipe, TCONP = 24.
EXHPEM		Typical value: 0.8
FEXHP		Typical value: 1.0

Table V-36: Namelist ROTORB, file ROTARY.INP: Variables' Descriptions

Variable	Type	Description
NRB	I*	Number of rotor bearings
DRB	R	Rotor bearing diameter (cm)
WRB	R	Load (weight) carried by the rotor bearing (rotor weight) (kg)
VRB	R	Rotor bearing oil viscosity (centipoise)
CRB	R	Rotor bearing clearance (cm)

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision. Numbers in parentheses denote the dimension (number of values) for the variable.

Table V-37: Namelist ROTORB, file ROTARY.INP: Variables' Values and Units

Variable	Units	Typical Values
NRB		Typical value: 2
DRB	cm	Typical value: 7 cm
WRB	kg	Typical value for a one rotor 40 in^3 engine: 4.5 kg
VRB	centipoise	Typical value: 10.4 centipoise
CRB	cm	Typical value: 0.01 cm

Table V-38: Namelist `MAINB`, file `ROTARY.INP`: Variables' Descriptions

Variable	Type	Description
NMB	I*	Number of main bearings
DMB	R	Main bearing diameter (cm)
WMB	R	Load (weight) carried by the main bearing (kg)
VMB	R	Main bearing oil viscosity (centipoise)
CMB	R	Main bearing clearance (cm)

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision. Numbers in parentheses denote the dimension (number of values) for the variable.

Table V-39: Namelist `MAINB`, file `ROTARY.INP`: Variables' Values and Units

Variable	Units	Typical Values
NMB		Typical value: 2
DMB	cm	Typical value: 5 cm
WMB	kg	Typical value for a one rotor 40 in^3 engine: 6 kg
VMB	centipoise	Typical value: 10.4 centipoise
CMB	cm	Typical value: 0.01 cm

Table V-40: Namelist NLWG, file ROTARY.INP: Variables' Descriptions

Variable	Type	Description
PWG1	R*	Wastegate cracking pressure (atm)**
PWG2	R	Intake manifold pressure at which the wastegate is fully open (atm)
AWG	R	Wastegate area (cm^2)
CDWG	R	Wastegate discharge coefficient

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision. Numbers in parentheses denote the dimension (number of values) for the variable.

** See Figure III-3

Table V-41: Namelist NLWG, file ROTARY.INP: Variables' Values and Units

Variable	Units	Typical Values
PWG1	atm	Dependent on turbocharger turbine. Typical value: 1.8 atm.
PWG2	atm	Dependent on turbocharger turbine. Typical value: 2.4 atm.
AWG	cm^2	Typical value: 0.05 cm^2
CDWG		Typical value: 1.0

Table V-42: Namelists HPROF, SPROF and RPROF, file ROTARY.INP: Variables' Descriptions

Variable	Type	Description
THSEG*	R(30)**	The only variable in namelist HPROF. THSEG(I) is the trochoid housing temperature for the midpoint of trochoid housing segment I. Crank angles corresponding to housing segment midpoints are given in section V-B.
TSSEG	R(30)	The only variable in namelist SPROF, TSSEG(I) is the side housing temperature for the midpoint of side housing segment I. Crank angles corresponding to housing segment midpoints are given in section V-B.
TRSEG	R(30)	The only variable in namelist RPROF, TRSEG(I) is the rotor face temperature history for the cycle. Crank angles corresponding to TRSEG entries are found in section V-B.

* An example for THSEG. THSEG is used only when IHTPRO = 1. Let THSEG = 350., 350., 350., 351., 351., 352., 352., 353., 355., 358., 363., 369., 375., 386., 399., 410., 422., 465., 465., 463., 460., 455., 445., 428., 416., 401., 376., 361., 358., 350. and let the intake port begin to open (TIPO, θ_{ipo}) at -620°. Then, at -602°, the housing temperature is 350 K. At -566°, the housing temperature is 350 K. At -530°, the housing temperature is 350 K. At -494°, the housing temperature is 351 K. At -458°, the housing temperature is 351 K. At -422°, the housing temperature is 352 K. At -386°, the housing temperature is 352 K. At -350°, the housing temperature is 353 K. At -314°, the housing temperature is 355 K. At -278°, the housing temperature is 358 K. At -242°, the housing temperature is 363 K etc..

** In variable types, I denotes integer, L denotes logical and R denotes real, single precision. Numbers in parentheses denote the dimension (number of values) for the variable.

Table V-43: Sample of Input File HHEAT.INP

```
&HOUSI1 NHML=3,
 HHCOOL=30*150.0,
 HTCOOL=30*350.0,
 THSEG=450.0,450.0,450.0,450.0,450.0,450.0,450.0,450.0,450.0,450.0,
       450.0,450.0,450.0,450.0,450.0,450.0,450.0,450.0,670.0,700.0,
       700.0,675.0,650.0,625.0,600.0,575.0,550.0,525.0,500.0,475.0
&END
&HOUSI2 HTHIK=1.25,5.0,5.0, HCOND=240.0,240.0,240.0 &END
&HOUSI3 TSAT=400.0, NTUBES=30, TCONL=0.416, CBOIL=12.546,
       DTUBES=1.5 &END
```

Table V-44: Namelist HOUS1, file HHEAT.INP: Variables' Descriptions

Variable	Type	Description
NHML	I*	Number of trochoid housing layers
HHCOOL	R(30)	Guesses for the 30 coolant side heat transfer coefficients ($\frac{W}{m^2K}$).
HTCOOL	R(30)	Coolant (liquid) temperature (K) at the entrance of the coolant passages
THSEG	R(30)	Guesses for the 30 trochoid housing hot gas side surface temperatures (K).

Table V-45: Namelist HOUS1, file HHEAT.INP: Variables' Values and Units

Variable	Units	Typical Values
NHML		1, 2 or 3
HHCOOL	$\frac{W}{m^2K}$	Example: HHCOOL = 158., 153., 151., 150., 150., 150., 150., 150., 150., 150., 155., 162., 168., 178., 190., 210., 223., 250., 271., 270., 263., 240., 223., 197., 188., 175., 169., 166., 162., 160.
HTCOOL	K	Example: HTCOOL = 325., 325.
THSEG	K	Example: THSEG = 400., 400.

Table V-46: Namelist HOUS2, file HHEAT.INP: Variables' Descriptions

Variable	Type	Description
HTHIK	R(3)*	Thicknesses of layers which make up the trochoid housing (mm). Note: the maximum number of layers is three.
HCOND	R	Thermal conductivities for the trochoid housing layers ($\frac{W}{mK}$). Note: HCOND should have three values, even if there is only one layer.

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision. Numbers in parentheses denote the dimension (number of values) for the variable.

Table V-47: Namelist HOUS2, file HHEAT.INP: Variables' Values and Units

Variable	Units	Typical Values
HTHIK	mm	For a housing made of a 10 mm aluminum layer coated with a thin (1 mm) low heat rejection material, HTHIK = 1., 10., 0. For an 11 mm all aluminum housing, HTHIK = 11., 0., 0.
HCOND	$\frac{W}{mK}$	For a housing made of a 10 mm aluminum layer coated with a thin (1 mm) low heat rejection material, HCOND = 1.5, 240., 240. Note that three values were given, even though there are only two layers. For an 11 mm thick all aluminum housing, HCOND = 240., 240., 240.

Table V-48: Namelist HOUS3, file HHEAT.INP: Variables' Descriptions

Variable	Type	Description
TSAT	R*	Coolant saturation temperature (K)
NTUBES	I	Number of coolant tubes around the trochoid housing (used to estimate coolant flow rate in the coolant passages)
TCONL	R	Coolant (liquid) thermal conductivity ($\frac{\mathrm{W}}{\mathrm{mK}}$).
CBOIL	R	Constant used to calculate boiling heat transfer rate in the coolant passages. Used in the expression:

$$q''_B = C_{boil}(T_{ts} - T_{sat})^3 \tag{28}$$

Variable	Type	Description
DTUBES	R	Coolant passage diameter (cm).
DTBIG	R	Constant used in calculating boiling heat transfer rate

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision. Numbers in parentheses denote the dimension (number of values) for the variable.

Table V-49: Namelist HOUS3, file HHEAT.INP: Variables' Values and Units

Variable	Units	Typical Values
TSAT	K	400 K for a 50/50 water/ethylene glycol mixture
NTUBES		Typical value: 30
TCONL	$\frac{\mathrm{W}}{\mathrm{mK}}$	0.416 for 50/50 water/ethylene glycol mixture
CBOIL		Typical value: 12.546
DTUBES	cm	Typical value: 1.5
DTBIG		Use 1000.

Table V-50: Sample of Input File SHEAT.INP

```
&SIDE1
   NSML   = 2,
   SHCOOL = 30*600.0,
   STCOOL = 30*300.0,
   TSSEG  = 30*350.0
&END
&SIDE2 STHIK=1.25,10.0,0.0, SCOND=240.0,240.0,240.0 &END
```

Table V-51: Namelist `SIDE1`, file `SHEAT.INP`: Variables' Descriptions

Variable	Type	Description
`NSML`	I*	Number of layers that make up the side housing
`SHCOOL`	R(30)	Coolant-side heat transfer coefficient ($\frac{W}{m^2K}$). Recall: the side housings are air-cooled. The user provides the coolant side heat transfer coefficient which is not changed during execution.
`STCOOL`	R(30)	Coolant temperature (on side wall exterior) (K).
`TSSEG`	R(30)	Guesses for side wall temperature at the 30 locations described in section III-?

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision. Numbers in parentheses denote the dimension (number of values) for the variable.

Table V-52: Namelist `SIDE1`, file `SHEAT.INP`: Variables' Values and Units

Variable	Units	Typical Values
`NSML`		1, 2 or 3
`SHCOOL`	$\frac{W}{m^2K}$	Example: `SHCOOL` = 250., 250.
`STCOOL`	K	Example: `STCOOL` = 350., 350.
`TSSEG`	K	Example: `TSSEG` = 350., 350., 350., 350., 350., 350., 350., 355., 370., 379., 391., 401., 405., 408., 408., 407., 405., 402., 398., 391., 380., 370., 360., 355., 350., 350., 350., 350., 350., 350.

Table V-53: Namelist SIDE2, file SHEAT.INP: Variables' Descriptions

Variable	Type	Description
STHIK	R(3)*	Thickness of the layers that make up the side housing (mm).
SCOND	R	Thermal conductivities of the layers making up the side housing ($\frac{W}{mK}$). All values of SCOND should be nonzero, even if the layer doesn't exist.

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision. Numbers in parentheses denote the dimension (number of values) for the variable.

Table V-54: Namelist SIDE2, file SHEAT.INP: Variables' Values and Units

Variable	Units	Typical Values
STHIK	mm	For a housing made of a 10 mm aluminum layer coated with a thin (1 mm) low heat rejection material, STHIK = 1., 10., 0. For an 11 mm all aluminum housing, STHIK = 11., 0., 0.
SCOND	$\frac{W}{mK}$	For a housing made of a 10 mm aluminum layer coated with a thin (1 mm) low heat rejection material, SCOND = 1.5, 240., 240. Note that three values were given, even though there are only two layers. For an 11 mm thick all aluminum housing, SCOND = 240., 240., 240.

Table V-55: Sample of Input File RHEAT.INP

```
&ROTIN1 TROTI=400.0, NRML=2, RHCOOL=2000.0, RTCOOL=325.0 &END
&ROTIN2 RTHIK=0.00125,0.01,0.0, RCOND=60.0,60.0,60.0 &END
```

Table V-56: Namelist ROTIN1, file RHEAT.INP: Variables' Descriptions

Variable	Type	Description
TROTI	R*	Guess at rotor face temperature (K).
NRML	I	Number of layers making up the rotor (1, 2 or 3)
RHCOOL	R	Coolant (oil) side heat transfer coefficient ($\frac{W}{m^2K}$). This value is not varied from cycle to cycle.
RTCOOL	R	Coolant (oil) temperature (K).

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision. Numbers in parentheses denote the dimension (number of values) for the variable.

Table V-57: Namelist ROTIN1, file RHEAT.INP: Variables' Values and Units

Variable	Units	Typical Values
TROTI	K	Typical value: 500K
NRML		1, 2 or 3
RHCOOL	$\frac{W}{m^2K}$	Typical value: 1200 $\frac{W}{m^2K}$
RTCOOL	K	Typical value: 325 K.

Table V-58: Namelist ROTIN2, file RHEAT.INP: Variables' Descriptions

Variable	Type	Description
RTHIK	R(3)*	Thickness of the layers that make up the rotor face(mm).
RCOND	R	Thermal conductivities of the layers making up the rotor face ($\frac{W}{mK}$). All values of RCOND should be nonzero, even if the layer doesn't exist.

* In variable types, I denotes integer, L denotes logical and R denotes real, single precision. Numbers in parentheses denote the dimension (number of values) for the variable.

Table V-59: Namelist ROTIN2, file RHEAT.INP: Variables' Values and Units

Variable	Units	Typical Values
RTHIK	mm	For a rotor made of a 10 mm iron layer coated with a thin (1 mm) low heat rejection material, RTHIK = 1., 10., 0. For an 11 mm all iron rotor face, RTHIK = 11., 0., 0.
RCOND	$\frac{W}{mK}$	For a rotor made of a 10 mm iron layer coated with a thin (1 mm) low heat rejection material, RCOND = 1.5, 50.7, 50.7 Note that three values were given, even though there are only two layers. For an 11 mm thick all iron rotor, RCOND = 50.7, 50.7, 50.7

Table V-60: Sample Compressor Flow Table

```
1001        COMPRESSOR FLOW MAP FOR RCEMAP USER'S GUIDE
ANGL  1        0.00
SPED  7       46.20    69.80    83.90    96.30   105.50   113.70   120.40
R     7       1.100    1.200    1.300    1.400    1.500    1.600    1.700
FLOW 7       0.0575   0.0813   0.1044   0.1286   0.1510   0.1720   0.1904
FLOW 7       0.0954   0.1285   0.1589   0.1861   0.2148   0.2426   0.2702
FLOW 7       0.1415   0.1771   0.2130   0.2460   0.2840   0.3125   0.3437
FLOW 7       0.1963   0.2304   0.2695   0.2993   0.3345   0.3633   0.3888
FLOW 7       0.2470   0.2875   0.3219   0.3499   0.3764   0.3996   0.4220
FLOW 7       0.2857   0.3191   0.3542   0.3862   0.4082   0.4278   0.4441
FLOW 7       0.3081   0.3489   0.3854   0.4165   0.4299   0.4426   0.4506
EOT
```

Table V-61: Sample Compressor Pressure Ratio Table

```
1003        PRESSURE RATIO MAP FOR RCEMAP USER'S GUIDE
ANGL  1        0.00
SPED  7       46.20    69.80    83.90    96.30   105.50   113.70   120.40
R     7       1.100    1.200    1.300    1.400    1.500    1.600    1.700
PR    7      1.2864   1.2879   1.2802   1.2556   1.2341   1.2045   1.1719
PR    7      1.5558   1.5673   1.5528   1.5193   1.4798   1.4245   1.3611
PR    7      1.8213   1.8506   1.8312   1.7819   1.7128   1.6374   1.5374
PR    7      2.1426   2.1759   2.1506   2.0912   1.9853   1.8771   1.7680
PR    7      2.4758   2.4753   2.4101   2.3159   2.2078   2.0717   1.9228
PR    7      2.7959   2.7764   2.6973   2.5444   2.3934   2.2254   2.0405
PR    7      3.1396   3.0914   2.9525   2.7161   2.5132   2.2904   2.0695
EOT
```

Table V-62: Sample Compressor Efficiency Table

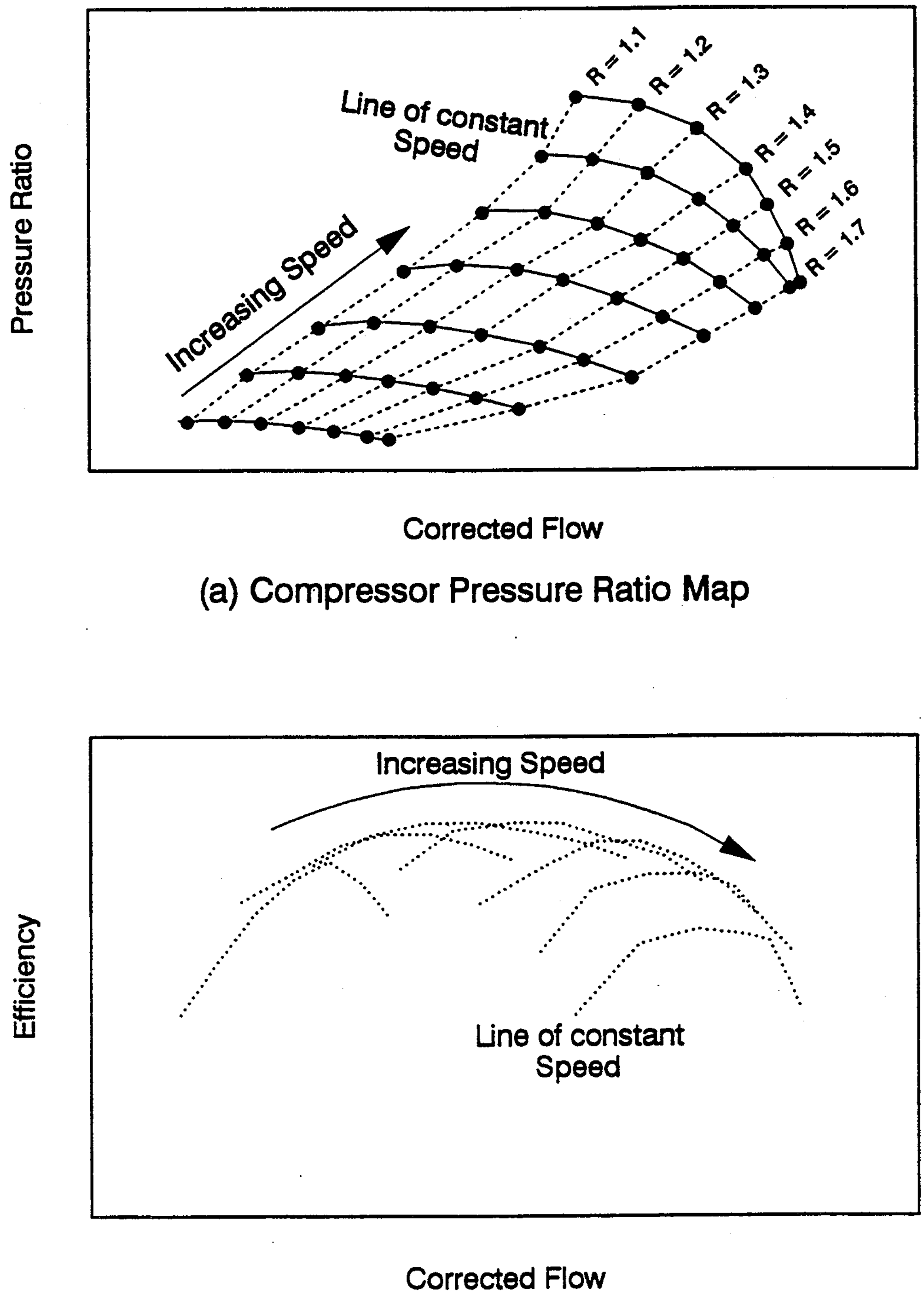
```
 1002       EFFICIENCY MAP FOR RCEMAP USER'S GUIDE
ANGL  1        0.00
SPED  7       46.20      69.80      83.90      96.30     105.50     113.70     120.40
R     7       1.100      1.200      1.300      1.400      1.500      1.600      1.700
EFF   7     0.56669    0.61105    0.65089    0.66913    0.69417    0.67557    0.64654
EFF   7     0.66065    0.68461    0.70845    0.71068    0.71773    0.70858    0.69463
EFF   7     0.69177    0.71628    0.72679    0.72716    0.71832    0.71052    0.69550
EFF   7     0.68888    0.72087    0.72711    0.72682    0.71131    0.69937    0.67701
EFF   7     0.65918    0.71078    0.71158    0.71142    0.69721    0.67794    0.65037
EFF   7     0.61853    0.69030    0.68362    0.68345    0.67312    0.64249    0.61891
EFF   7     0.56694    0.65447    0.63526    0.62548    0.62767    0.59396    0.56944
EOT
```

Table V-63: Sample Turbine Flow Table

```
 5001       TURBINE CORRECTED FLOW MAP
ANGL  1        0.00
SPED  8       25.60      38.70      46.60      53.50      58.70      63.00      66.80
              70.00
PR    7      1.1280     1.1513     1.1715     1.1937     1.2246     1.2577     1.2854
FLOW  7      0.1246     0.1550     0.1857     0.2112     0.2423     0.2723     0.2992
PR    7      1.3298     1.3758     1.4316     1.4873     1.5603     1.6399     1.7376
FLOW  7      0.2835     0.3162     0.3482     0.3724     0.4056     0.4315     0.4598
PR    7      1.6047     1.6820     1.7605     1.8196     1.9079     2.0036     2.1079
FLOW  7      0.3980     0.4245     0.4451     0.4652     0.4881     0.5087     0.5305
PR    7      1.9404     2.0055     2.1347     2.1987     2.2693     2.4174     2.4950
FLOW  7      0.4725     0.4853     0.5106     0.5233     0.5336     0.5544     0.5648
PR    7      2.2389     2.3497     2.4499     2.5405     2.6558     2.7603     2.8876
FLOW  7      0.5080     0.5261     0.5392     0.5502     0.5622     0.5754     0.5822
PR    7      2.5310     2.6571     2.7681     2.8661     2.9967     3.1206     3.2479
FLOW  7      0.5307     0.5446     0.5551     0.5628     0.5728     0.5788     0.5829
PR    7      2.8653     2.9915     3.1154     3.2341     3.3656     3.4983     3.5987
FLOW  7      0.5472     0.5531     0.5613     0.5677     0.5726     0.5755     0.5759
PR    7      3.0143     3.1211     3.2430     3.3444     3.4642     3.5785     3.6853
FLOW  7      0.5353     0.5403     0.5444     0.5482     0.5502     0.5521     0.5543
EOT
```

Table V-64: Sample Turbine Efficiency Table

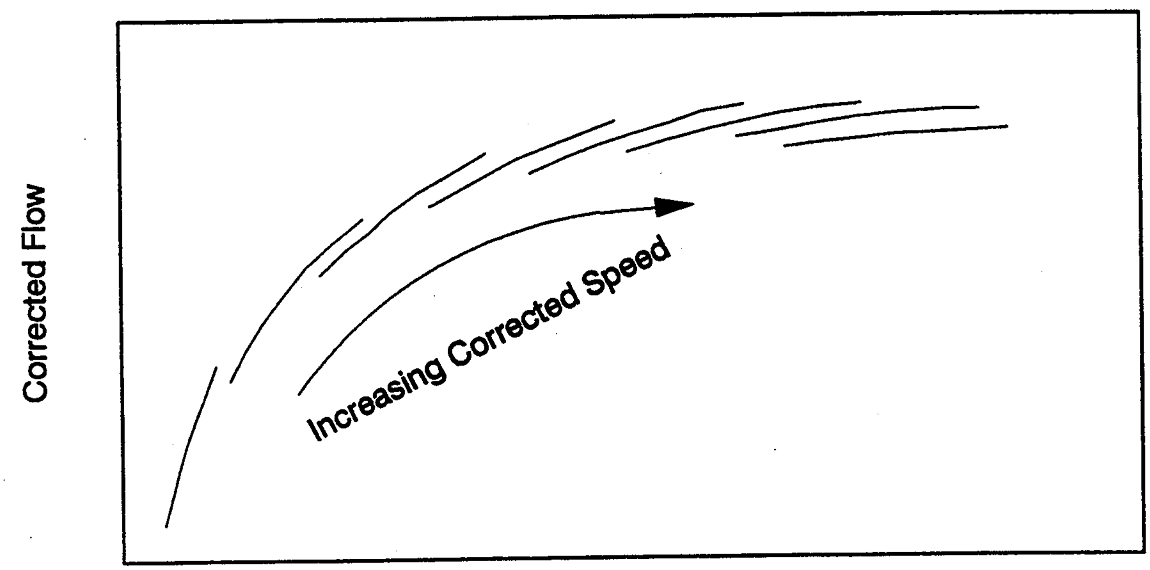
```
5002      TURBINE EFFICIENCY MAP
ANGL  1      0.00
SPED  8     25.60    38.70    46.60    53.50    58.70    63.00    66.80
            70.00
PR    9    1.0078   1.1046   1.1206   1.1835   1.1935   1.2157   1.2441
           1.2643   1.2869
EFF   9    0.7383   0.7583   0.7675   0.7672   0.7613   0.7376   0.6954
           0.6690   0.6391
PR    9    1.2785   1.3753   1.3889   1.4740   1.5034   1.5835   1.6198
           1.6419   1.6676
EFF   9    0.7046   0.7315   0.7381   0.7373   0.7280   0.6970   0.6805
           0.6627   0.6400
PR    9    1.5197   1.5874   1.6445   1.7007   1.7660   1.8199   1.8929
           1.9423   1.9951
EFF   9    0.6923   0.7122   0.7271   0.7315   0.7264   0.7126   0.6878
           0.6649   0.6392
PR    9    1.8289   1.9138   1.9593   2.0430   2.1268   2.2151   2.2760
           2.3179   2.3824
EFF   9    0.6863   0.7085   0.7136   0.7083   0.6972   0.6807   0.6681
           0.6516   0.6318
PR    9    2.1133   2.2159   2.2992   2.3829   2.4700   2.5580   2.6255
           2.7018   2.7595
EFF   9    0.6733   0.6905   0.6941   0.6883   0.6791   0.6704   0.6603
           0.6500   0.6397
PR    9    2.4729   2.5679   2.6328   2.7109   2.7944   2.8511   2.9208
           2.9950   3.0745
EFF   9    0.6518   0.6643   0.6723   0.6751   0.6694   0.6608   0.6495
           0.6371   0.6178
PR    9    2.8274   2.9159   3.0262   3.1075   3.1867   3.2608   3.3152
           3.3840   3.4354
EFF   9    0.6226   0.6334   0.6445   0.6455   0.6373   0.6282   0.6196
           0.6070   0.5914
PR    9    2.9633   3.0953   3.2297   3.3490   3.4457   3.5098   3.6287
           3.6264   3.6766
EFF   9    0.6048   0.6119   0.6163   0.6157   0.6102   0.6025   0.5944
           0.5845   0.5728
EOT
```



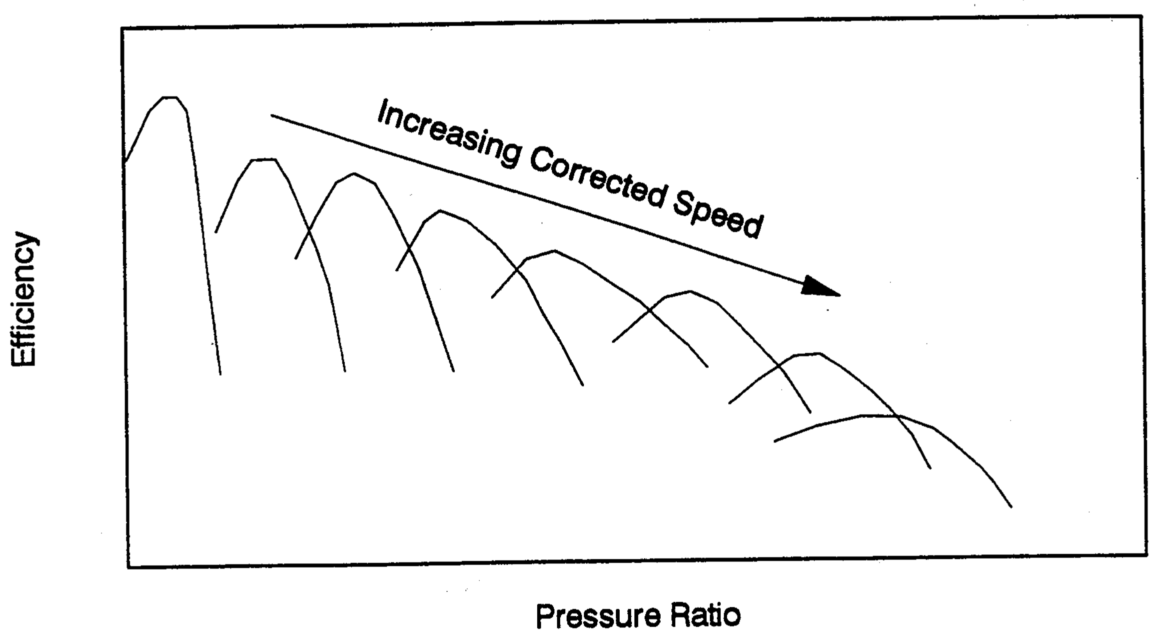
(a) Compressor Pressure Ratio Map

(b) Compressor Efficiency Map

Figure V-1: Typical Compressor Map



(a) Turbine Flow Rate Map



(b) Turbine Efficiency Map

Figure V-2: Typical Turbine Maps

VI OUTPUT

Users have different interests when running RCEMAP. They may be interested in generating an engine performance map showing "global" engine performance, without much attention to detail. They may be interested in the crank-angle-by-crank-angle performance of the engine, such as heat flux to the walls or chamber pressure. Most quantities of interest are output to one file or another. RCEMAP produces up to 11 output files, though the user probably won't need all the output files for all runs. Table VI-1 offers a brief description of available output files. More complete descriptions are found in this section of the user's guide. Now that the user can set up input files and execute RCEMAP, it is time to describe what performance data are produced and where they are found.

RCEMAP can produce more output than the average user needs. However, there are means to limit outputs to those which suit the user's needs. Output is controlled through the variables found in namelist NLWRIT in the input file ROTARY.INP (see Tables V-20 and V-21 on pages 67–67 for descriptions of the contents of namelist NLWRIT). All output files except the relatively small file RCEMAP.OUT can be "turned-off". The switch that turns-on and turns-off output files is the variable LDEBUG in namelist NLWRIT. LDEBUG is a logical variable of dimension 15, although only 10 of its values are used. Each of LDEBUG's values corresponds to an output file unit number (e.g., LDEBUG(1) corresponds to output unit 1). Output files and their unit numbers are listed in Table VI-1. To activate an output unit, set the corresponding value of LDEBUG equal to .TRUE.. To suppress output, make the corresponding LDEBUG value .FALSE..

Most performance data are found in the relatively short file RSHORT.OUT; this is the file the authors use most often. RCEMAP produces two versions of RSHORT.OUT. The complete version not only contains performance data but also echoes the input data. The shortened version provides only a modicum of echoed input data with the performance data. To make RCEMAP write the brief version of RSHORT.OUT, set LBRIEF (input file ROTARY.INP, namelist NLWRIT) equal to .TRUE.. The user also has a choice between SI and USCS units for the output in RSHORT.OUT. When variable LSI equals .TRUE., outputs are in SI units. Otherwise, they are in USCS units.

Another way to limit output data is provided by the variables TPRINT and TPRINX. These variables fix the interval at which crank-angle-by-crank-angle data are output. TPRINT sets the interval for the intake, compression and exhaust processes. TPRINX sets the interval during combustion and expansion. The units for both variables are crank angle degrees. They are found in namelist NLWRIT of input file ROTARY.INP.

The remainder of this section is devoted to more detailed descriptions of each output file and examples of the various outputs. The examples in the following descriptions were generated for a turbocharged engine run at 6000 rpm, equivalence ratio equal to 0.6 and at sea level. This run is referred to as example three. The input files for exmaple three are found in Tables VI-2 – VI-6. The input file TURB.DAT was omitted, since the data contained therein are proprietary.

VI-A `RCEMAP.OUT`

`RCEMAP` generates the output file `RCEMAP.OUT` for every run. Nine quantities are output to `RCEMAP.OUT`: air mass flow rate, fuel mass flow rate, brake power, fraction of the fuel energy to the coolant, friction power (including ancillary losses), mass averaged exhaust gas temperature, thermal efficiency and brake specific fuel consumption. All of these quantities are presented in tabular form, as functions of engine speed and equivalence ratio.

`RCEMAP.OUT` for example three is shown in Table VI-7. Tables IV-3 and IV-6 are additional examples of `RCEMAP.OUT` (for exmaples 1 and 2).

VI-B `ROTARY.OUT` (Output Unit 1)

The most comprehensive output file is `ROTARY.OUT`. `ROTARY.OUT` contains three types of outputs. First, input variables (engine geometry, mathematical constants etc.) are echoed. Next, there are crank-angle-by-crank-angle outputs such as volume, pressure temperature and composition and combustion progress (combustion progress is zero before any fuel is burnt and is one when all the fuel is burnt). Finally, `ROTARY.OUT` presents performance data including bmep, bsfc, cooling heat loss and volumetric efficiency. `ROTARY.OUT` contains no information about turbocharger operation. `ROTARY.OUT` for the turbocharged engine example is found in Table VI-8.

VI-C `ROTARY.PLT` (Output Unit 2)

With this file, the user can easily make plots such as P-V diagrams and chamber temperature and pressure histories. `ROTARY.PLT` contains columns of crank angle, chamber volume, pressure, temperature, mass and combustion progress. Combustion progress is a dimensionless variable which measures the completeness of combustion: when combustion progress is zero, no "new" fuel has been burned. When combustion progress equals one, combustion is complete. `ROTARY.PLT` for example three is shown in Table VI-9. Two plots were made from the data in `ROTARY.PLT`: a P-V diagram (Figure VI-1) and a time history of chamber pressure (Figure VI-2).

VI-D `RSHORT.OUT` (Output Unit 3)

The authors use the two output files `RCEMAP.OUT` and `RSHORT.OUT` most frequently. The shorter of the two, `RSHORT.OUT` presents comprehensive engine and turbocharger performance data. There are several sections to `RSHORT.OUT`. There is an echo of input data and a convergence summary. A seal and bearing friction section provides a summary of friction and ancillary losses. Heat transfer data includes peak component temperatures and the fraction of fuel energy lost to the coolant. There is a chamber properties section which gives peak pressure and temperature and exhaust pressure and temperature. Mean effective pressure, power, efficiency and sfc are provided next. A summary of mass flow through the engine describes how much air and fuel passed through the engine, how much was trapped and how much leaked. Finally, turbocharger performance is summarized. Table VI-10 is `RSHORT.OUT` for example three.

VI-E `RFLOW.PLT` (Output Unit 4)

`RFLOW.PLT` contains crank-angle-by-crank-angle intake and exhaust flow descriptions. It has columns of crank angle, intake mass flow rate, exhaust mass flow rate, integrated intake and exhaust flows, intake manifold pressure and intake manifold temperature. `RFLOW.PLT` for example three is provided in Table VI-11. Figure VI-3 shows mass flow rate through the intake port as a function of crank angle.

VI-F `RHEAT.PLT` (Output Unit 5)

Heat transfer to the trochoid housing, the side housing and the rotor face is described crank-angle-by-crank-angle in `RHEAT.PLT`. The file is columns of crank angle, gas temperature, gas velocity used to calculate heat transfer coefficient, heat transfer coefficient, total heat transfer rate to the engine structure, and individual heat fluxes to the trochoid housing, side housing and rotor. `RHEAT.PLT` for example three in Table VI-12. Heat flux to the rotor, side housing and trochoid housing are plotted as functions of crank angle in Figure VI-4.

VI-G `RMASS.PLT` (Output Unit 6)

`RMASS.PLT` presents columns of crank angle, chamber mass, mass fraction of burnt and unburnt gases and equivalence ratio. Table VI-13 shows `RMASS.PLT` for example three. Burnt and unburnt mass fraction are plotted against crank angle in Figure VI-5.

VI-G `RHOUS.PLT` (Output Unit 7)

Average trochoid housing wall temperature and coolant properties are provided in `RHOUS.PLT`. Wall temperatures are only calculated at 36 locations on the housing. For these 36 locations, `RHOUS` gives crank angle, chamber gas temperature, hot-gas-side heat transfer coefficient, hot-gas-side trochoid housing temperature, coolant-side wall temperature, coolant-side heat transfer coefficient and coolant temperature. `RHOUS.PLT` for example three is found in Table VI-14. Figure VI-6 is a graph showing trochoid housing surface temperature as a function of crank angle.

VI-H `RCREV.PLT` (Output Unit 8)

`RCREV.PLT` is a rarely-used file which shows crank-angle-by-crank-angle leakage and crevice flows. It contains columns of crank angle, lead and lag crevice masses, lead and lag leakage flows and lead and lag crevice mass composition. Table VI-15 shows `RCREV.PLT` for example three.

VI-I `RFRIC.PLT` (Output Unit 9)

Friction-related outputs are summarized in `RFRIC.PLT`. First, crank-angle-by-crank-angle lead apex seal friction is described. There are columns of crank angle, distance travelled by the apex seal, speed of the apex seal, chamber pressure, lead chamber pressure, apex seal force normal to the trochoid housing and friction force. Next, side seal, oil seal and bearing friction are described. A sample of `RFRIC.PLT` is found in Table VI-16. Figure VI-7 is a plot of the normal force the apex seal exerts on the trochoid housing versus crank angle. Note that there are two positions around which the seal normal force is low and the seal may be subject to lift-off.

VI-J `RSIDE.PLT` (Output Unit 10)

The last output file, `RSIDE.PLT`, contains side housing wall temperature and heat transfer information. There are columns of crank angle, chamber gas temperature, hot-gas-side heat transfer coefficient, "old" and "new" hot-gas-side wall temperature, "old" and "new" coolant-side wall temperature and coolant-side heat transfer coefficient and coolant temperature. "Old" and "new" refer to second-to-last and last cycles in the simulation. Recall that the side housing is air cooled and the coolant temperature and heat transfer coefficient are constant during the cycle. `RSIDE.PLT` for example three is found in Table VI-17.

Table VI-1: RCEMAP Output Files

File	Unit No.	Description
RCEMAP.OUT		Engine maps
ROTARY.OUT	1	Comprehensive output file
ROTARY.PLT	2	Crank-angle-by-crank-angle P-V-T-m data
RSHORT.PLT	3	Cycle performance data (short file)
RFLOW.PLT	4	Intake/exhaust flow
RHEAT.PLT	5	Heat transfer data
RMASS.PLT	6	Chamber mass and composition
RHOUS.PLT	7	Trochoid housing wall temperature and cooling
RCREV.PLT	8	Crevice and leakage flows
RFRIC.PLT	9	Apex seal friction
RSIDE.PLT	10	Side housing wall temperature and cooling

Table VI-2: Input File `RCEMAP.INP` for Example 3

```
&RUNRCE
   NROTOR  = 1
   IFUELT  = 1
   PIM     = 1.5
   PEM     = 1.3
   NALT    = 1
   ALTL    = 0.
   ALTH    = 0.
   NRPM    = 1
   RPML    = 6500.
   RPMH    = 6500.
   NPHI    = 1
   PHIL    = 0.6
   PHIH    = 0.6
&END
```

Table VI-3: Input File ROTARY.INP for Example 3

```
$NLCASE
   ICASE  = 3
   IDAY   = 30
   IMONTH = 9
   IYEAR  = 1991
   MAXITS = 16
$END
$NLOPCS
   LFIRE  = .T.
   LTCHAR = .T.
   L2C    = .F.
   IFUELT = 1
   EGR    = 0.0
   TEGR   = 300.
   ANCIL1 = 0.3680
   ANCIL2 = 0.1319
   ANCIL3 = 0.0059
   ITABC1 = 1
   ITABC2 = 2
   ITABC3 = 3
   ITABC4 = 14
   ITABC5 = 15
   ITABC6 = 16
   ITABT1 = 4
   ITABT2 = 5
   RCORR  = 545., 13.94, 519., 14.688, 519., 14.688
$END
$NLGEOM
   ECCEN  = 1.5
   ROTRAD = 10.5
   DEPTH  = 7.
   VFLANK = 50.
   SZOVER = 0.08
   CLRNCE = 0.064
   AREALK = 0.01
   CREVOL = 0.4
$END
$NLHREL
   TSPARK = -10.
   TMAX   = 15.
   XBZERO = 0.0
   XBSTOP = 0.98
   DQDTMX = 0.05
```

```
$END
$NLPORT
   IPA    = 13.8
   EPA    = 9.
   CDIP   = 0.60
   CDEP   = 0.65
   TIPO   = -620.1
   TIPC   = -240.1
   TEPO   = 199.1
   TEPC   = 588.5
   THIPO  = 40.
   THEPO  = 40.
$END
$NLHEAT
   IHTPRO = 3.
   IRTPRO = 3.
   ISTPRO = 3.
   TROTI  = 310.
   TSIDI  = 310.
   THOUSI = 310.
   CONHT  = 0.037
   EXPHT  = 0.8
   CON1   = 0.75
   CON2   = 1.5
   LCOUET = .F.
   ALFF   = 2.0
   PRNTUR = 0.7
$END
$NLIMAN
   LPIM   = .T.
   VIM    = 2550.
   TIM    = 310.
$END
$NLEMAN
   LPEM   = .T.
   VEM    = 400.
   PEXH   = 0.95
$END
$NLWRIT
   LDEBUG = .T.,.T.,.T.,.T.,.T.,.T.,.T.,.T.,.T.,.T.,
      .F.,.F.,.F.,.F.,.F.
   LBRIEF = .T.
   TPRINT = 20.
   TPRINX = 10.
```

```
$END
$NLCONV
   TCONV  = 0.01
   PCONV  = 0.01
   XMCONV = 0.01
   TRCONV = 0.01
   THCONV = 0.01
   PMCONV = 0.01
   EMCONV = 0.01
$END
&NLAPEX
   ABASE = 0.18
   AFRC1 = 0.07
   AFRC2 = 0.13
   AHEIG = 0.77
   AMASS = 35.0
   ARAD  = 0.0813
   FSPRI = 33.36
&END
&NLSIDE
   SIDEB  = 0.18
   SIDEH  = 0.24
   SIDECF = 0.07
   SIDEF  = 75.
&END
&NLOILS
   SOILB  = 0.15
   SOILCF = 0.06
   SOILF  = 22.0
   SOILR  = 6.0
   SOILP  = 2.0
&END
&EXHFL
   EPTHIK = 0.25
   EXHPL  = 10.
   TPOUT  = 300.
   TCONP  = 24.
   EXHPEM = 0.8
   FEXHP  = 1.0
&END
&ROTORB
   NRB    = 2
   DRB    = 7.81
   WRB    = 4.50
```

```
   VRB    = 10.4
   CRB    = 0.01016
&END
&MAINB
   NMB    = 2
   DMB    = 4.60
   WMB    = 6.36
   VMB    = 10.4
   CMB    = 0.01016
&END
&ACOOL
  DPAC   = 0.03
  HAFTC  = 400.0
  TACIN  = 310.0
  AAFTC  = 0.40
&END
&ICOOL
  DPIC   = 0.03
  HINTC  = 400.0
  TICIN  = 300.0
  AINTC  = 0.40
&END
$NLWG
   PWG1   = 6002.1
   PWG2   = 6002.4
   AWG    = 0.07
   CDWG   = 0.7
&END
```

Table VI-4: Input File HHEAT.INP for Example 3

```
&HOUSI1 NHML=3,
 HHCOOL=30*150.0,
 HTCOOL=30*350.0,
 THSEG=450.0,450.0,450.0,450.0,450.0,450.0,450.0,450.0,450.0,450.0,
       450.0,450.0,450.0,450.0,450.0,450.0,450.0,450.0,670.0,700.0,
       700.0,675.0,650.0,625.0,600.0,575.0,550.0,525.0,500.0,475.0
&END
&HOUSI2 HTHIK=1.25,5.0,5.0, HCOND=240.0,240.0,240.0 &END
&HOUSI3 TSAT=400.0, NTUBES=30, TCONL=0.416, CBOIL=12.546,
       DTUBES=1.5 &END
```

Table VI-5: Input File SHEAT.INP for Example 3

```
&ROTIN1 TROTI=400.0, NRML=2, RHCOOL=2000.0, RTCOOL=325.0 &END
&ROTIN2 RTHIK=0.00125,0.01,0.0, RCOND=60.0,60.0,60.0 &END
```

Table VI-6: Input File RHEAT.INP for Example 3

```
&SIDE1
   NSML   = 2,
   SHCOOL = 30*600.0,
   STCOOL = 30*300.0,
   TSSEG  = 30*350.0
&END
&SIDE2 STHIK=1.25,10.0,0.0, SCOND=240.0,240.0,240.0 &END
```

Table VI-7: Output File RCEMAP.OUT for Example 3

```
>>>>> RCE PERFORMANCE MAP ROUTINE OUTPUT


>>>>> ENGINE PERFORMANCE PARAMETERS FOR:

      INTAKE MANIFOLD PRESSURE    =     0.0000 ATM
      INTAKE MANIFOLD TEMPERATURE =   334.792 K
      EXHAUST MANIFOLD PRESSURE   =     1.3000 ATM


   >> AIR MASS FLOW RATE (LB/HR)

PHI\RPM     6500.00
-----------------------------------

 0.600        951.19


   >> FUEL MASS FLOW RATE (LB/HR)

PHI\RPM     6500.00
-----------------------------------

 0.600         32.30


   >> BRAKE POWER (BHP)

PHI\RPM     6500.00
-----------------------------------

 0.600         72.29


   >> HEAT TRANSFER TO COOLANT (% FUEL ENERGY)

PHI\RPM     6500.00
```

```
-----------------------------------

 0.600        13.18


   >> FRICTION POWER (FHP)

PHI\RPM     6500.00
-----------------------------------

 0.600        19.65


   >> MASS AVERAGED EXHAUST GAS TEMP (DEG R)

PHI\RPM     6500.00
-----------------------------------

 0.600      1714.61


   >> THERMAL EFFICIENCY

PHI\RPM     6500.00
-----------------------------------

 0.600       37.187


   >> BRAKE SPECIFIC FUEL CONSUMPTION (LB/HP-HR)

PHI\RPM     6500.00
-----------------------------------

 0.600        0.447
```

M.I.T. ZERO-DIMENSIONAL WANKEL ENGINE CYCLE SIMULATION

1

>>>>> START OF INTAKE PROCESS

CA (DEG)	P (ATM)	TEMP (K)	MIN (G)	MEX (G)	VIV (CM/SEC)	VEV (CM/SEC)	XI (-)	Q DOT (KJ/DEG)	WORK (KJ)	IMF	IFG
-620.1	1.2923	825.41	0.00000	0.00000	0.0		0.43333		0.000000		
-620.1	1.2923	825.41	0.00000	0.00000	0.0	136.0	0.43333	0.000029	0.000000	0	0
-600.0	1.3236	732.44	0.02111	0.03625	7114.2	14091.4	0.54479	0.000022	-0.006425	1	0
-580.0	1.3951	588.48	0.06854	0.08410	4751.2	13962.3	0.71731	0.000013	-0.011510	1	0
-560.0	1.3811	478.63	0.12262	0.14035	5311.8	12478.8	0.83504	0.000005	-0.014744	1	0
-540.0	1.3451	406.06	0.18721	0.20005	6405.8	11295.6	0.91141	-0.000002	-0.015824	1	0
-521.0	1.3239	369.13	0.25823	0.25433	6798.4	11207.0	0.95164	-0.000005	-0.014881	1	0
-520.0	1.3246	368.01	0.26195	0.25670	6766.3	11238.4	0.95300	-0.000005	-0.014780	1	0
-500.0	1.3901	358.37	0.32572	0.28045	4141.8	-4091.1	0.96908	-0.000006	-0.011637	1	0
-480.0	1.3700	350.66	0.37458	0.27855	5279.5	0.0	0.97534	-0.000007	-0.006468	1	0
-460.0	1.3345	343.00	0.43930	0.27855	6425.2	0.0	0.98056	-0.000007	0.000207	1	0
-440.0	1.2997	336.94	0.51438	0.27855	7218.2	0.0	0.98436	-0.000007	0.007947	1	0
-420.0	1.2712	332.42	0.59615	0.27855	7712.3	0.0	0.98706	-0.000007	0.016302	1	0
-400.0	1.2523	329.18	0.68147	0.27855	7943.2	0.0	0.98900	-0.000007	0.024848	1	0
-380.0	1.2447	327.04	0.76760	0.27855	7935.9	0.0	0.99042	-0.000007	0.033189	1	0
-360.0	1.2492	325.91	0.85201	0.27855	7682.6	0.0	0.99147	-0.000007	0.040956	1	0
-340.0	1.2736	327.14	0.93145	0.27855	6954.0	0.0	0.99168	-0.000007	0.047809	1	0
-320.0	1.3147	331.64	0.99951	0.27855	5690.2	0.0	0.99084	-0.000006	0.053453	1	0
-300.0	1.3536	335.09	1.05384	0.27855	4357.2	0.0	0.99037	-0.000006	0.057514	1	0
-280.0	1.3937	337.86	1.09250	0.27855	2688.9	0.0	0.99022	-0.000006	0.059659	1	0
-260.1	1.4299	340.29	1.10837	0.27855	926.0	0.0	0.99010	-0.000008	0.059660	1	0
-256.7	1.4362	340.73	1.10887	0.27855	-233.6	0.0	0.99007	-0.000008	0.059440	1	0
-240.0	1.4775	343.59	1.10634	0.27855	0.0	0.0	0.98993	-0.000009	0.057377	0	0
-240.0	1.4775	343.59	1.10634	0.27855	0.0	0.0	0.98993	-0.000009	0.057377	0	0
-240.1	1.4775	343.59	1.10634	0.27855	0.0	0.0	0.98993	-0.000009	0.057377	0	2

1

>>>>> START OF COMPRESSION PROCESS

Table VI-8: Output File ROTARY.OUT for Example 3

CA (DEG)	P (ATM)	TEMP (K)		Q DOT (KJ/DEG)	WORK (KJ)	IFG
-240.1	1.4775	343.59	-0.00001	0.057377		2
-240.0	1.4779	343.61		-0.000009	0.057360	0
-220.0	1.5823	350.49		-0.000010	0.052701	0
-200.0	1.7528	361.06		-0.000010	0.045434	0
-180.0	2.0127	375.87		-0.000013	0.035208	0
-160.0	2.4004	395.61		-0.000015	0.021513	0
-140.0	2.9802	421.18		-0.000017	0.003643	0
-120.0	3.8573	453.53		-0.000015	-0.019313	0
-100.0	5.2047	494.14		-0.000007	-0.048411	0
-80.0	7.3109	544.73		0.000012	-0.084607	0
-60.0	10.5302	604.07		0.000042	-0.127843	0
-40.0	15.0166	667.43		0.000086	-0.174664	0
-20.0	19.7807	721.25		0.000135	-0.214641	0

1

>>>>> START OF COMBUSTION AND EXPANSION PROCESSES

CA (DEG)	P (ATM)	TEMP (K)	XBURND (-)	Q DOT (KJ/DEG)	WORK (KJ)	IFG
-10.0	21.3945	737.57	0.01090	0.000151	-0.226791	2
0.0	27.8224	944.01	0.07421	0.000325	-0.231274	0
10.0	42.2746	1471.77	0.26365	0.001012	-0.223953	0
20.0	55.5806	2056.19	0.51659	0.002169	-0.193893	0
30.0	53.5125	2168.12	0.59874	0.002383	-0.140051	0
40.0	46.8647	2126.44	0.61864	0.002130	-0.072479	0
50.0	39.7516	2047.07	0.62298	0.001802	0.000895	0
60.0	33.3453	1960.86	0.62353	0.001508	0.074779	0
70.0	27.9335	1877.32	0.62324	0.001265	0.145947	0
80.0	23.4947	1799.59	0.62285	0.001068	0.212633	0
90.0	19.9035	1728.57	0.62254	0.000909	0.274030	0
100.0	17.0127	1664.31	0.62233	0.000782	0.329916	0
110.0	14.6860	1606.47	0.62222	0.000679	0.380399	0
120.0	12.8081	1554.57	0.62219	0.000596	0.425759	0
130.0	11.2856	1508.01	0.62218	0.000527	0.466350	0
140.0	10.0446	1466.24	0.62217	0.000471	0.502548	0
150.0	9.0295	1428.93	0.62219	0.000424	0.534703	0
160.0	8.1950	1395.59	0.62219	0.000387	0.563160	0
170.0	7.5071	1365.91	0.62219	0.000356	0.588219	0
180.0	6.9393	1339.58	0.62219	0.000331	0.610148	0
190.0	6.4706	1316.36	0.62219	0.000310	0.629184	0

1

>>>>> START OF EXHAUST PROCESS

CA	P	TEMP	MEX	VEV	Q DOT	WORK	IFG

(DEG)	(ATM)	(K)	(G)	(M/SEC)	(KJ/DEG)	(KJ)	
199.1	6.1202	1297.90	0.27855	0.0	0.000299	0.644009	2
200.0	6.0881	1296.23	0.27866	264.8	0.000197	0.645376	0
220.0	5.1561	1245.94	0.32075	259.8	0.000174	0.670135	0
240.0	4.0228	1175.49	0.44829	252.6	0.000141	0.684267	0
260.0	3.1077	1105.66	0.57272	245.2	0.000113	0.689916	0
280.0	2.4960	1048.03	0.67320	235.9	0.000091	0.689996	0
300.0	2.0810	1000.37	0.75579	224.1	0.000076	0.686486	0
320.0	1.7971	961.17	0.82474	209.5	0.000064	0.680639	0
340.0	1.6074	929.20	0.88311	193.2	0.000055	0.673259	0
360.0	1.4870	903.22	0.93343	177.5	0.000049	0.664870	0
380.0	1.4253	881.56	0.97851	167.5	0.000044	0.655828	0
400.0	1.4057	868.66	1.02174	164.0	0.000040	0.646373	0
420.0	1.3863	856.07	1.06406	159.4	0.000037	0.636905	0
440.0	1.3523	840.43	1.10467	151.1	0.000033	0.627988	0
459.9	1.2963	820.48	1.14170	136.4	0.000028	0.620223	0

```
>>>>>> OUTPUT FROM MIT DISC RCE PERFORMANCE MODEL

CASE  3,  30 SEP  1991

>>>>>> BRIEF ECHO OF ENGINE GEOMTERY AND OPERATING CONDITIONS

       NUMBER OF ROTORS                            =         1
       ENGINE SPEED (RPM)                          =   6500.00
       EQUIVALENCE RATIO (-)                       =     0.600
       DISPLACED VOLUME (CC)                       =    577.16
       AVERAGE INTAKE MANIFOLD PRESSURE (ATM)      =      1.42
       AVERAGE INTAKE MANIFOLD TEMPERATURE (K)     =    322.82
       EXHAUST GAS RECIRCULATION (%)               =      0.00
       AVERAGE EXHAUST MANIFOLD PRESSURE (ATM)     =      1.16
       NORMALIZED MAX COMB HEAT RELEASE RATE       =    0.0500
       ANGLE FOR MAX HEAT RELEASE RATE             =     15.00
       HEAT RELEASE RATE DECAY CONSTANT            =    7.1000
       FUEL USED IS ISOOCTANE
       INTAKE MANIFOLD PROPERTIES ARE VARIABLE
```

```
>>>>>> CONVERGENCE SUMMARY FOR ITERATION 12 OUT OF 16 ALLOWED

       CYCLE INITIAL CHAMBER PRESSURE (ATM)     =      1.296
       CHANGE IN INITIAL PRESSURE (%)           =       0.31

       CYCLE INITIAL CHAMBER TEMPERATURE (K)    =     820.48
       CHANGE IN INITIAL TEMPERATURE (%)        =      -0.60

       AVERAGE INTAKE MANIFOLD PRESSURE (ATM)   =      1.417
       CHANGE IN AVG INTAKE MAN PRESS (%)       =       0.57

       AVERAGE EXHAUST MANIFOLD PRESSURE (ATM)  =      1.288
       CHANGE IN AVG EXHAUST MAN PRESS (%)      =       0.33

       CYCLE INITIAL INT MANIFOLD PRESS (ATM)   =      1.432
```

```
CHANGE IN INITIAL INTAKE MAN PRESS (%)  =       0.61

CYCLE INITIAL EXH MANIFOLD PRESS (ATM)  =       1.097
CHANGE IN INITIAL EXHAUST MAN PRESS (%) =      -0.23

CURRENT CYCLE INTAKE MASS (G)           =       1.106
CURRENT CYCLE EXHAUST MASS (G)          =       1.142
MASS LEAKED TO LEAD CREVICE (G)         =       0.001
MASS LEAKED TO LAG CREVICE (G)          =      -0.001
CYCLE MASS OF FUEL INJECTED (G)         =     0.03757
INITIAL MASS IN THE CHAMBER (G)         =       0.114
DIFF IN INTAKE AND EXHAUST MASS (%)     =       0.19

MAX TROCHOID HOUSING TEMPERATURE (K)    =      474.20
MAX CHANGE IN TROCH HOUSING TEMP (%)    =        0.31
NEW ROTOR FACE TEMPERATURE (K)          =      453.87
CHANGE IN ROTOR FACE TEMPERATURE (%)    =        0.25
```

```
INTEGRATED AVERAGE HEAT TRANSFER PER AREA TO
THE ENGINE COMPONENTS

HEAT TRANSFER PER AREA, ROTOR FACE (W/M2)     =  4.094E+08
HEAT TRANSFER PER AREA, SIDE HOUSING (W/M2)   =  4.094E+08
HEAT TRANSFER PER AREA, TROCH. HOUSING (W/M2) =  4.094E+08
```


1

```
>--------------+--------------<
>                             <
>     ENGINE PERFORMANCE      <
>                             <
>--------------+--------------<
```

```
-->  FRICTION POWER, ALL APEX SEALS (3 PER ROTOR)
                          (KW)          ---->      1.281
                          (HP)          ---->      1.717
-->  FRICTION POWER, ALL SIDE SEALS (6 PER ROTOR)
                          (KW)          ---->      1.744
                          (HP)          ---->      2.338
-->  FRICTION POWER, ALL OIL SEALS (2 PER ROTOR)
                          (KW)          ---->      0.391
                          (HP)          ---->      0.523
-->  FRICTION POWER, ALL MAIN BEARINGS
                          (KW)          ---->      0.426
                          (HP)          ---->      0.571
-->  FRICTION POWER, ALL ROTOR BEARINGS
                          (KW)          ---->      1.474
                          (HP)          ---->      1.976
-->  FRICTION POWER FOR ANCILLARY COMPONENTS
                          (KW)          ---->      9.342
```

```
                     (HP)            ---->     12.523
-->  FRICTION POWER FOR ALL SEALS AND BEARINGS
                     (KW)            ---->      5.316
                     (HP)            ---->      7.126
-->  TOTAL FRICTION POWER
                     (KW)            ---->     14.658
                     (HP)            ---->     19.649

>>>>> HEAT TRANSFER

-->  MAXIMUM TROCHOID HOUSING SURFACE TEMPERATURE
                     (K)             ---->      474.2
                     (DEG F)         ---->      393.9
     MAX SURFACE TEMP OCCURS NEAR  117.90 DEG
-->  AVERAGE ROTOR SURFACE TEMPERATURE
                     (K)             ---->      453.9
                     (DEG F)         ---->      357.3
-->  TEMPERATURE DROP IN THE EXHAUST MANFOLD
                     (K)             ---->        2.6
                     (DEG F)         ---->        4.6
-->  (HEAT TRANSFER PER CYCLE)/(MASS OF FUEL TIMES LHV)
                     (%)             ---->       13.2
-->  HEAT TRANSFER TO ROTOR FACE, ONE CYCLE
                     (KJ)            ---->     0.0953
                     (BTU)           ---->     0.0903
-->  HEAT TRANSFER TO SIDE HOUSING, ONE CYCLE
                     (KJ)            ---->     0.0185
                     (BTU)           ---->     0.0176
-->  HEAT TRANSFER TO TROCHOID HOUSING, ONE CYCLE
                     (KJ)            ---->     0.1060
                     (BTU)           ---->     0.1005

>>>>> CHAMBER PROPERTIES

-->  MAXIMUM CHAMBER PRESSURE
                     (KPA)           ---->     5672.9
                     (PSI)           ---->     822.78
                     (ATM)           ---->      55.99
     MAX PRESSURE OCCURS AT   22.00 DEG
-->  MAXIMUM CHAMBER TEMPERATURE
                     (K)             ---->     2168.1
                     (DEG F)         ---->     3442.9
     MAX TEMPERATURE OCCURS AT   30.00 DEG
-->  MASS AVERAGED EXHAUST GAS TEMPERATURE
                     (K)             ---->      952.6
                     (DEG F)         ---->     1254.9
-->  TIME AVERAGED EXHAUST GAS TEMPERATURE
                     (K)             ---->      807.2
                     (DEG F)         ---->      993.3
-->  TIME AVERAGED INTAKE MANIFOLD PRESSURE
                     (KPA)           ---->      143.6
                     (PSI)           ---->      20.83
                     (ATM)           ---->       1.42
-->  TIME AVERAGED INTAKE MANIFOLD TEMPERATURE
                     (K)             ---->     322.82
                     (DEG F)         ---->     121.41
-->  MAXIMUM INTAKE MANIFOLD PRESSURE
                     (KPA)           ---->      146.9
                     (PSI)           ---->       1.45
                     (ATM)           ---->      21.31
```

```
     MAX PRESSURE OCCURS AT -239.39 DEG
-->  TIME AVERAGED EXHAUST MANIFOLD PRESSURE
                         (KPA)         ---->     130.5
                         (PSI)         ---->     18.92
                         (ATM)         ---->      1.29
-->  TIME AVERAGED EXHAUST MANIFOLD TEMPERATURE
                         (K)           ---->    871.44
                         (DEG F)       ---->   1108.92

>>>>> MEAN EFFECTIVE PRESSURE AND POWER

-->  GROSS INDICATED MEAN EFFECTIVE PRESSURE (IMEP)
                         (KPA)         ---->    1097.0
                         (PSI)         ---->    159.10
                         (ATM)         ---->     10.83
-->  PUMPING MEAN EFFECTIVE PRESSURE (PMEP)
                         (KPA)         ---->     -22.4
                         (PSI)         ---->     -3.24
                         (ATM)         ---->     -0.22
-->  FRICTION MEAN EFFECTIVE PRESSURE (FMEP)
                         (KPA)         ---->     234.4
                         (PSI)         ---->     34.00
                         (ATM)         ---->      2.31
-->  BRAKE MEAN EFFECTIVE PRESSURE (BMEP)
                         (KPA)         ---->     862.5
                         (PSI)         ---->    125.10
                         (ATM)         ---->      8.51
-->  INDICATED POWER, ONE ROTOR (IHP)
                         (KW)          ---->     68.59
                         (HP)          ---->     91.94
-->  FRICTION POWER, ONE ROTOR (FHP)
                         (KW)          ---->     14.66
                         (HP)          ---->     19.65
-->  BRAKE POWER ONE ROTOR (BHP)
                         (KW)          ---->     53.93
                         (HP)          ---->     72.29

>>>>> EFFICIENCY AND FUEL CONSUMPTION

-->  VOLUMETRIC EFFIC BASED ON INTAKE MANIFOLD PRESS
                         (%)           ---->      98.0
-->  TRAPPING EFFICIENCY
                         (%)           ---->      88.0
-->  GROSS INDICATED THERMAL EFFICIENCY
                         (%)           ---->      38.0
-->  NET INDICATED THERMAL EFFICIENCY
                         (%)           ---->      37.2
-->  GROSS INDICATED SPECIFIC FUEL CONSUMPTION (ISFC)
                         (G/IKW-HR)    ---->      214.
                         (LB/HP-HR)    ---->     0.351
-->  BRAKE SPECIFIC FUEL CONSUMPTION (BSFC)
                         (G/IKW-HR)    ---->      272.
                         (LB/HP-HR)    ---->     0.447

>>>>> COMBUSTION

-->  IGNITION DELAY (0 - 10%)
                         (CRANK ANGLE) ---->     10.00
```

```
                        (MS)               ---->        0.26
  -->  BURN DURATION (10 - 90%)
                        (CRANK ANGLE)      ---->       25.99
                        (MS)               ---->        0.67

>>>>> MASS FLOW

  -->  MASS IN CYLINDER AT TIME INTAKE PORT OPENS
                        (G)                ---->        0.114
                        (LBM)              ---->      0.00025
  -->  MASS IN CYLINDER AT TIME INTAKE PORT CLOSES
                        (G)                ---->        0.957
                        (LBM)              ---->      0.00211
  -->  MASS THROUGH THE INTAKE PORT (ONE CHAMBER)
                        (G/CYCLE)          ---->        1.106
                        (LBM/CYCLE)        ---->      0.00244
  -->  MASS THROUGH THE EXHAUST PORT (ONE CHAMBER)
                        (G/CYCLE)          ---->        1.142
                        (LBM/CYCLE)        ---->      0.00252
  -->  MASS OF FUEL INJECTED (ONE CHAMBER)
                        (G/CYCLE)          ---->        0.038
                        (LBM/CYCLE)        ---->      0.00008
  -->  MASS LEAKED TO THE LEAD CREVICE (ONE CHAMBER)
                        (G/CYCLE)          ---->        0.001
                        (LBM/CYCLE)        ---->      0.00000
  -->  MASS LEAKED TO THE LAG CREVICE (ONE CHAMBER)
                        (G/CYCLE)          ---->       -0.001
                        (LBM/CYCLE)        ---->      0.00000
  -->  TOTAL AIR TO ALL ROTORS FOR 1 CYCLE
                        (G/CYCLE)          ---->      3.31903
                        (LBM/CYCLE)        ---->      0.00732
  -->  TOTAL AIR MASS FLOW RATE (TO ALL ROTORS)
                        (G/SEC)            ---->       119.85
                        (LBM/HR)           ---->        951.2
  -->  TOTAL FUEL MASS FLOW RATE (TO ALL ROTORS)
                        (G/SEC)            ---->        4.070
                        (LBM/HR)           ---->         32.3
  -->  RESIDUAL FRACTION                   ---->        0.010

>>>>> WORK, HEAT TRANSFER AND POWER

  -->  HEAT TRANS TO STRUCTURE DURING COMBUST. AND EXPAN.
                        (KJ/CYCLE)         ---->        0.211
                        (BTU/CYCLE)        ---->        0.200
  -->  INDICATED SHAFT WORK DURING COMBUST. AND EXPANS.
                        (KJ/CYCLE)         ---->        0.633
                        (BTU/CYCLE)        ---->        0.600
  -->  HEAT TRANSFER TO STRUCTURE FOR ONE CHAMBER
                        (KJ/CYCLE)         ---->        0.220
                        (BTU/CYCLE)        ---->        0.208
  -->  INDICATED SHAFT WORK FOR ONE CHAMBER
                        (KJ/CYCLE)         ---->        0.620
                        (BTU/CYCLE)        ---->        0.588
  -->  INDICATED POWER (INCLUDING ALL ROTORS)
                        (KW)               ---->       67.191
                        (HP)               ---->       90.069

 HEATI   =   -0.000902 KJ (TIPO   -   -270)
 WORKI   =    0.057377 KJ
```

```
HEATC   =    0.003672 KJ (-270  -  TSPARK)
WORKC   =   -0.284168 KJ

HEATCE  =    0.210664 KJ (TSPARK - TEPO)
WORKCE  =    0.633130 KJ

HEATE   =    0.010071 KJ (+270  -  TIPO)
WORKE   =   -0.070284 KJ
```

```
TOTAL ENTHALPY IN / CYCLE    =   0.36125 KJ
TOTAL ENTHALPY OUT / CYCLE   =  -0.56118 KJ
TOTAL HEAT LOSS / CYCLE      =   0.21983 KJ
TOTAL WORK OUTPUT / CYCLE    =   0.62022 KJ
HEAT LOSS TO CREVICE/CYCLE   =   0.00000 KJ

"LOST" FUEL ENERGY           =   0.00046 KJ
NET ENERGY GAIN / CYCLE      =  -0.00091 KJ
(ENERGY GAIN)/(ENTHALPY IN)  =  -0.25123 %
(ENERGY GAIN)/(MFUEL*LHV)    =  -0.05442 %
```

Table VI-9: Output File ROTARY.PLT for Example 3

MIT CODE PLOT FILE ROTARY.PLT: INSTANTANEOUS CHAMBER PROPERTIES

CRANK ANGLE	VOLUME (CC)	PRESSURE (ATM)	TEMPERATURE (K)	MASS (G)	COMBUSTION PROGRESS (0-->1)
-620.1	208.5	1.292	825.41	0.114	0.000
-600.0	159.5	1.324	732.44	0.101	0.000
-580.0	122.7	1.395	588.48	0.102	0.000
-560.0	99.8	1.381	478.63	0.101	0.000
-540.0	92.0	1.345	406.06	0.107	0.000
-521.0	99.0	1.324	369.13	0.125	0.000
-520.0	99.8	1.325	368.01	0.126	0.000
-500.0	122.7	1.390	358.37	0.167	0.000
-480.0	159.5	1.370	350.66	0.219	0.000
-460.0	208.3	1.334	343.00	0.284	0.000
-440.0	266.3	1.300	336.94	0.361	0.000
-420.0	330.5	1.271	332.42	0.444	0.000
-400.0	397.4	1.252	329.18	0.531	0.000
-380.0	463.4	1.245	327.04	0.619	0.000
-360.0	524.9	1.249	325.91	0.706	0.000
-340.0	578.6	1.274	327.14	0.791	0.000
-320.0	621.7	1.315	331.64	0.865	0.000
-300.0	651.8	1.354	335.09	0.924	0.000
-280.0	667.2	1.394	337.86	0.966	0.000
-260.1	667.3	1.430	340.29	0.984	0.000
-256.7	665.8	1.436	340.73	0.985	0.000
-240.0	651.8	1.478	343.59	0.984	0.000
-240.0	651.8	1.478	343.59	0.984	0.000
-240.0	651.8	1.478	343.61	0.984	0.000
-220.0	621.7	1.582	350.49	0.985	0.000
-200.0	578.6	1.753	361.06	0.986	0.000
-180.0	524.9	2.013	375.87	0.986	0.000
-160.0	463.4	2.400	395.61	0.987	0.000
-140.0	397.4	2.980	421.18	0.987	0.000
-120.0	330.5	3.857	453.53	0.987	0.000
-100.0	266.3	5.205	494.14	0.984	0.000
-80.0	208.3	7.311	544.73	0.981	0.000
-60.0	159.5	10.530	604.07	0.976	0.000
-40.0	122.7	15.017	667.43	0.969	0.000
-20.0	99.8	19.781	721.25	0.961	0.000

0.0	92.0	27.822	944.01	0.952	0.100
10.0	94.0	42.275	1471.77	0.946	0.400
20.0	99.8	55.581	2056.19	0.943	0.804
30.0	109.4	53.513	2168.12	0.944	0.937
40.0	122.7	46.865	2126.44	0.945	0.969
50.0	139.5	39.752	2047.07	0.946	0.977
60.0	159.5	33.345	1960.86	0.948	0.979
70.0	182.6	27.933	1877.32	0.949	0.980
80.0	208.3	23.495	1799.59	0.950	0.980
90.0	236.3	19.904	1728.57	0.951	0.980
100.0	266.3	17.013	1664.31	0.951	0.980
110.0	297.8	14.686	1606.47	0.951	0.980
120.0	330.5	12.808	1554.57	0.951	0.980
130.0	363.8	11.286	1508.01	0.951	0.980
140.0	397.4	10.045	1466.24	0.951	0.980
150.0	430.7	9.030	1428.93	0.951	0.980
160.0	463.4	8.195	1395.59	0.951	0.980
170.0	494.9	7.507	1365.91	0.950	0.980
180.0	524.9	6.939	1339.58	0.950	0.980
190.0	552.9	6.471	1316.36	0.950	0.980
200.0	578.6	6.088	1296.23	0.949	0.980
220.0	621.7	5.156	1245.94	0.898	0.980
240.0	651.8	4.023	1175.49	0.779	0.980
260.0	667.2	3.108	1105.66	0.655	0.980
280.0	667.2	2.497	1048.03	0.555	0.980
300.0	651.8	2.081	1000.37	0.473	0.980
320.0	621.7	1.797	961.17	0.406	0.980
340.0	578.6	1.607	929.20	0.350	0.980
360.0	524.9	1.487	903.22	0.302	0.980
380.0	463.4	1.425	881.56	0.262	0.980
400.0	397.4	1.406	868.66	0.225	0.980
420.0	330.5	1.386	856.07	0.187	0.980
440.0	266.3	1.352	840.43	0.150	0.980
459.9	208.5	1.296	820.48	0.115	0.980

Table VI-10: Output File RSHORT.OUT for Example 3

```
>>>>>> OUTPUT FROM MIT DISC RCE PERFORMANCE MODEL

CASE  3,  30 SEP  1991


>>>>>> BRIEF ECHO OF ENGINE GEOMTERY AND OPERATING CONDITIONS

       NUMBER OF ROTORS                          =          1
       ENGINE SPEED (RPM)                        =    6500.00
       EQUIVALENCE RATIO (-)                     =      0.600
       DISPLACED VOLUME (CC)                     =     577.16
       AVERAGE INTAKE MANIFOLD PRESSURE (ATM)    =       1.42
       AVERAGE INTAKE MANIFOLD TEMPERATURE (K)   =     322.82
       EXHAUST GAS RECIRCULATION (%)             =       0.00
       AVERAGE EXHAUST MANIFOLD PRESSURE (ATM)   =       1.16
       NORMALIZED MAX COMB HEAT RELEASE RATE     =     0.0500
       ANGLE FOR MAX HEAT RELEASE RATE           =      15.00
       HEAT RELEASE RATE DECAY CONSTANT          =     7.1000
       FUEL USED IS ISOOCTANE
       INTAKE MANIFOLD PROPERTIES ARE VARIABLE


>>>>>> CONVERGENCE SUMMARY FOR ITERATION 12 OUT OF 16 ALLOWED

       CYCLE INITIAL CHAMBER PRESSURE (ATM)      =      1.296
       CHANGE IN INITIAL PRESSURE (%)            =       0.31

       CYCLE INITIAL CHAMBER TEMPERATURE (K)     =     820.48
       CHANGE IN INITIAL TEMPERATURE (%)         =      -0.60

       AVERAGE INTAKE MANIFOLD PRESSURE (ATM)    =      1.417
       CHANGE IN AVG INTAKE MAN PRESS (%)        =       0.57

       AVERAGE EXHAUST MANIFOLD PRESSURE (ATM)   =      1.288
       CHANGE IN AVG EXHAUST MAN PRESS (%)       =       0.33

       CYCLE INITIAL INT MANIFOLD PRESS (ATM)    =      1.432
       CHANGE IN INITIAL INTAKE MAN PRESS (%)    =       0.61
```

```
CYCLE INITIAL EXH MANIFOLD PRESS (ATM)  =      1.097
CHANGE IN INITIAL EXHAUST MAN PRESS (%) =     -0.23

CURRENT CYCLE INTAKE MASS (G)           =      1.106
CURRENT CYCLE EXHAUST MASS (G)          =      1.142
MASS LEAKED TO LEAD CREVICE (G)         =      0.001
MASS LEAKED TO LAG CREVICE (G)          =     -0.001
CYCLE MASS OF FUEL INJECTED (G)         =    0.03757
INITIAL MASS IN THE CHAMBER (G)         =      0.114
DIFF IN INTAKE AND EXHAUST MASS (%)     =       0.19

MAX TROCHOID HOUSING TEMPERATURE (K)    =     474.20
MAX CHANGE IN TROCH HOUSING TEMP (%)    =       0.31
NEW ROTOR FACE TEMPERATURE (K)          =     453.87
CHANGE IN ROTOR FACE TEMPERATURE (%)    =       0.25


>>>>> SEAL AND BEARING FRICTION


    -->  FRICTION POWER, ALL APEX SEALS (3 PER ROTOR)
                           (KW)          ---->       1.281
                           (HP)          ---->       1.717
    -->  FRICTION POWER, ALL SIDE SEALS (6 PER ROTOR)
                           (KW)          ---->       1.744
                           (HP)          ---->       2.338
    -->  FRICTION POWER, ALL OIL SEALS (2 PER ROTOR)
                           (KW)          ---->       0.391
                           (HP)          ---->       0.523
    -->  FRICTION POWER, ALL MAIN BEARINGS
                           (KW)          ---->       0.426
                           (HP)          ---->       0.571
    -->  FRICTION POWER, ALL ROTOR BEARINGS
                           (KW)          ---->       1.474
                           (HP)          ---->       1.976
    -->  FRICTION POWER FOR ANCILLARY COMPONENTS
                           (KW)          ---->       9.342
                           (HP)          ---->      12.523
    -->  FRICTION POWER FOR ALL SEALS AND BEARINGS
                           (KW)          ---->       5.316
                           (HP)          ---->       7.126
    -->  TOTAL FRICTION POWER
                           (KW)          ---->      14.658
```

```
                         (HP)           ---->     19.649


>>>>> HEAT TRANSFER


   -->  MAXIMUM TROCHOID HOUSING SURFACE TEMPERATURE
                         (K)            ---->      474.2
                         (DEG F)        ---->      393.9
        MAX SURFACE TEMP OCCURS NEAR  117.90 DEG
   -->  AVERAGE ROTOR SURFACE TEMPERATURE
                         (K)            ---->      453.9
                         (DEG F)        ---->      357.3
   -->  TEMPERATURE DROP IN THE EXHAUST MANFOLD
                         (K)            ---->        2.6
                         (DEG F)        ---->        4.6
   -->  (HEAT TRANSFER PER CYCLE)/(MASS OF FUEL TIMES LHV)
                         (%)            ---->       13.2
   -->  HEAT TRANSFER TO ROTOR FACE, ONE CYCLE
                         (KJ)           ---->     0.0953
                         (BTU)          ---->     0.0903
   -->  HEAT TRANSFER TO SIDE HOUSING, ONE CYCLE
                         (KJ)           ---->     0.0185
                         (BTU)          ---->     0.0176
   -->  HEAT TRANSFER TO TROCHOID HOUSING, ONE CYCLE
                         (KJ)           ---->     0.1060
                         (BTU)          ---->     0.1005


>>>>> CHAMBER PROPERTIES


   -->  MAXIMUM CHAMBER PRESSURE
                         (KPA)          ---->     5672.9
                         (PSI)          ---->     822.78
                         (ATM)          ---->      55.99
        MAX PRESSURE OCCURS AT   22.00 DEG
   -->  MAXIMUM CHAMBER TEMPERATURE
                         (K)            ---->     2168.1
                         (DEG F)        ---->     3442.9
        MAX TEMPERATURE OCCURS AT   30.00 DEG
   -->  MASS AVERAGED EXHAUST GAS TEMPERATURE
                         (K)            ---->      952.6
                         (DEG F)        ---->     1254.9
```

```
-->  TIME AVERAGED EXHAUST GAS TEMPERATURE
                                  (K)            ---->      807.2
                                  (DEG F)        ---->      993.3
-->  TIME AVERAGED INTAKE MANIFOLD PRESSURE
                                  (KPA)          ---->      143.6
                                  (PSI)          ---->      20.83
                                  (ATM)          ---->       1.42
-->  TIME AVERAGED INTAKE MANIFOLD TEMPERATURE
                                  (K)            ---->     322.82
                                  (DEG F)        ---->     121.41
-->  MAXIMUM INTAKE MANIFOLD PRESSURE
                                  (KPA)          ---->      146.9
                                  (PSI)          ---->      21.31
                                  (ATM)          ---->       1.45
     MAX PRESSURE OCCURS AT -239.39 DEG
-->  TIME AVERAGED EXHAUST MANIFOLD PRESSURE
                                  (KPA)          ---->      130.5
                                  (PSI)          ---->      18.92
                                  (ATM)          ---->       1.29
-->  TIME AVERAGED EXHAUST MANIFOLD TEMPERATURE
                                  (K)            ---->     871.44
                                  (DEG F)        ---->    1108.92


>>>>> MEAN EFFECTIVE PRESSURE AND POWER


-->  GROSS INDICATED MEAN EFFECTIVE PRESSURE (IMEP)
                                  (KPA)          ---->     1097.0
                                  (PSI)          ---->     159.10
                                  (ATM)          ---->      10.83
-->  PUMPING MEAN EFFECTIVE PRESSURE (PMEP)
                                  (KPA)          ---->      -22.4
                                  (PSI)          ---->      -3.24
                                  (ATM)          ---->      -0.22
-->  FRICTION MEAN EFFECTIVE PRESSURE (FMEP)
                                  (KPA)          ---->      234.4
                                  (PSI)          ---->      34.00
                                  (ATM)          ---->       2.31
-->  BRAKE MEAN EFFECTIVE PRESSURE (BMEP)
                                  (KPA)          ---->      862.5
                                  (PSI)          ---->     125.10
                                  (ATM)          ---->       8.51
-->  INDICATED POWER, ONE ROTOR (IHP)
```

```
                    (KW)           ---->      68.59
                    (HP)           ---->      91.94
 -->  FRICTION POWER, ONE ROTOR (FHP)
                    (KW)           ---->      14.66
                    (HP)           ---->      19.65
 -->  BRAKE POWER ONE ROTOR (BHP)
                    (KW)           ---->      53.93
                    (HP)           ---->      72.29


>>>>> EFFICIENCY AND FUEL CONSUMPTION


 -->  VOLUMETRIC EFFIC BASED ON INTAKE MANIFOLD PRESS
                    (%)            ---->       98.0
 -->  TRAPPING EFFICIENCY
                    (%)            ---->       88.0
 -->  GROSS INDICATED THERMAL EFFICIENCY
                    (%)            ---->       38.0
 -->  NET INDICATED THERMAL EFFICIENCY
                    (%)            ---->       37.2
 -->  GROSS INDICATED SPECIFIC FUEL CONSUMPTION (ISFC)
                    (G/IKW-HR)     ---->       214.
                    (LB/HP-HR)     ---->      0.351
 -->  BRAKE SPECIFIC FUEL CONSUMPTION (BSFC)
                    (G/IKW-HR)     ---->       272.
                    (LB/HP-HR)     ---->      0.447


>>>>> COMBUSTION


 -->  IGNITION DELAY (0 - 10%)
                    (CRANK ANGLE)  ---->      10.00
                    (MS)           ---->       0.26
 -->  BURN DURATION (10 - 90%)
                    (CRANK ANGLE)  ---->      25.99
                    (MS)           ---->       0.67


>>>>> MASS FLOW


 -->  MASS IN CYLINDER AT TIME INTAKE PORT OPENS
```

```
                          (G)            ---->      0.114
                          (LBM)          ---->    0.00025
     -->  MASS IN CYLINDER AT TIME INTAKE PORT CLOSES
                          (G)            ---->      0.957
                          (LBM)          ---->    0.00211
     -->  MASS THROUGH THE INTAKE PORT (ONE CHAMBER)
                          (G/CYCLE)      ---->      1.106
                          (LBM/CYCLE)    ---->    0.00244
     -->  MASS THROUGH THE EXHAUST PORT (ONE CHAMBER)
                          (G/CYCLE)      ---->      1.142
                          (LBM/CYCLE)    ---->    0.00252
     -->  MASS OF FUEL INJECTED (ONE CHAMBER)
                          (G/CYCLE)      ---->      0.038
                          (LBM/CYCLE)    ---->    0.00008
     -->  MASS LEAKED TO THE LEAD CREVICE (ONE CHAMBER)
                          (G/CYCLE)      ---->      0.001
                          (LBM/CYCLE)    ---->    0.00000
     -->  MASS LEAKED TO THE LAG CREVICE (ONE CHAMBER)
                          (G/CYCLE)      ---->     -0.001
                          (LBM/CYCLE)    ---->    0.00000
     -->  TOTAL AIR TO ALL ROTORS FOR 1 CYCLE
                          (G/CYCLE)      ---->    3.31903
                          (LBM/CYCLE)    ---->    0.00732
     -->  TOTAL AIR MASS FLOW RATE (TO ALL ROTORS)
                          (G/SEC)        ---->     119.85
                          (LBM/HR)       ---->      951.2
     -->  TOTAL FUEL MASS FLOW RATE (TO ALL ROTORS)
                          (G/SEC)        ---->      4.070
                          (LBM/HR)       ---->       32.3
     -->  RESIDUAL FRACTION              ---->      0.010


>>>>> WORK, HEAT TRANSFER AND POWER


     -->  HEAT TRANS TO STRUCTURE DURING COMBUST. AND EXPAN.
                          (KJ/CYCLE)     ---->      0.211
                          (BTU/CYCLE)    ---->      0.200
     -->  INDICATED SHAFT WORK DURING COMBUST. AND EXPANS.
                          (KJ/CYCLE)     ---->      0.633
                          (BTU/CYCLE)    ---->      0.600
     -->  HEAT TRANSFER TO STRUCTURE FOR ONE CHAMBER
                          (KJ/CYCLE)     ---->      0.220
                          (BTU/CYCLE)    ---->      0.208
```

```
--> INDICATED SHAFT WORK FOR ONE CHAMBER
                     (KJ/CYCLE)     ---->     0.620
                     (BTU/CYCLE)    ---->     0.588
--> INDICATED POWER (INCLUDING ALL ROTORS)
                     (KW)           ---->    67.191
                     (HP)           ---->    90.069


COMPRESSOR MATCHING ROUTINE OUTPUT


>>> PROGRAM INPUTS
    COMPRESSOR FLOW MAP NUMBER             = 1
    COMPRESSOR EFFICIENCY MAP NUMBER       = 2
    COMPRESSOR PRESSURE RATIO MAP NUMBER   = 3
    TURBINE FLOW MAP NUMBER                = 4
    TURBINE EFFICIENCY MAP NUMBER          = 5
    COMPRESSOR INLET TEMPERATURE CORRECTION =   545.00 deg R
    COMPRESSOR INLET PRESSURE CORRECTION    =   13.940 psi
    TURBINE INLET TEMPERATURE CORRECTION    =   519.00 deg R
    TURBINE INLET PRESSURE CORRECTION       =   14.688 psi


>>> COMPRESSOR OPERATING CONDITIONS
    PRESSURE RATIO  =     1.414
    MAP INTERPOLATION R  =   1.4120
    CORRECTED FLOW (lbm/min)    =    0.244
    CORRECTED SPEED (rpm/1000) =   64.873
    EFFICIENCY (%)              =   70.415
    ACTUAL MASS FLOW (lbm/hr)  =   951.19
    ACTUAL SPEED (rpm)          =  63286.9
    POWER (hp)                  =  -6.8895


>>> TURBINE OPERATING CONDITIONS
    PRESSURE RATIO  =     1.267
    CORRECTED FLOW (lbm/min)     =    0.371
    CORRECTED SPEED (rpm/1000)  =   36.404
    EFFICIENCY (%)               =   73.042
    WASTEGATE FRACTION OPEN      =   0.0000
    WASTEGATE FLOW RATE (lb/hr) =     0.00
    % OF FLOW TO WASTEGATE       =    0.000
    ACTUAL MASS FLOW (lbm/hr)   =   983.49
    ACTUAL SPEED (rpm)           =  63286.9
```

POWER (hp) = 7.0305

>>> STATION TEMPERATURES AND PRESSURES AFTER 5 ITERATIONS

WORK ERROR = 2.046 %

STATION	TEMPERATURE (K)	PRESSURE (ATM)
1	288.1	1.000
2	330.5	1.414
2S	318.0	1.414
3	316.7	1.417
4	322.8	1.417
6	871.4	1.288
7	871.4	1.280
8	835.9	1.000
8S	822.7	1.000

MIT CODE PLOT FILE RFLOW.PLT: INTAKE AND EXHAUST FLOW (ONE ROTOR ONLY)

CRANK ANGLE (DEG)	INTAKE MASS FLOW (G/S)	EXHAUST MASS FLOW (G/S)	MASS THROUGH INTAKE PORT (G)	MASS THROUGH EXHAUST PORT (G)	INTAKE MANIFOLD PRESS (ATM)	INTAKE MANIFOLD TEMP (K)
-620.1	0.000	67.345	0.0000	0.0000	1.423	324.16
-600.0	76.880	80.236	0.0211	0.0363	1.442	325.26
-580.0	102.376	104.451	0.0685	0.0841	1.445	325.34
-560.0	114.449	113.743	0.1226	0.1403	1.444	325.18
-540.0	137.721	118.276	0.1872	0.2001	1.439	324.74
-521.0	145.577	93.729	0.2582	0.2543	1.431	324.08
-520.0	144.862	91.133	0.2620	0.2567	1.430	324.04
-500.0	88.580	-10.664	0.3257	0.2805	1.428	323.76
-480.0	113.215	0.000	0.3746	0.2786	1.432	323.95
-460.0	137.607	0.000	0.4393	0.2786	1.429	323.64
-440.0	154.040	0.000	0.5144	0.2786	1.421	323.04
-420.0	163.840	0.000	0.5961	0.2786	1.412	322.33
-400.0	167.953	0.000	0.6815	0.2786	1.402	321.61
-380.0	167.110	0.000	0.7676	0.2786	1.393	320.97
-360.0	161.269	0.000	0.8520	0.2786	1.387	320.47
-340.0	145.761	0.000	0.9315	0.2786	1.384	320.19
-320.0	119.446	0.000	0.9995	0.2786	1.386	320.28
-300.0	91.688	0.000	1.0538	0.2786	1.395	320.77
-280.0	56.998	0.000	1.0925	0.2786	1.409	321.63
-260.1	9.955	0.000	1.1084	0.2786	1.432	323.00
-256.7	-1.987	0.000	1.1089	0.2786	1.436	323.26
-240.0	0.000	0.000	1.1063	0.2786	1.449	323.98
-240.0	0.000	0.000	1.1063	0.2786	1.449	323.98
-240.0	0.000	0.000	1.1063	0.2786	1.449	323.98
-220.0	0.000	0.000	1.1063	0.2786	1.449	323.98
-200.0	0.000	0.000	1.1063	0.2786	1.449	323.98
-180.0	0.000	0.000	1.1063	0.2786	1.449	323.98
-160.0	0.000	0.000	1.1063	0.2786	1.449	323.98
-140.0	0.000	0.000	1.1063	0.2786	1.449	323.98
-120.0	0.000	0.000	1.1063	0.2786	1.449	323.98
-100.0	0.000	0.000	1.1063	0.2786	1.449	323.98
-80.0	0.000	0.000	1.1063	0.2786	1.449	323.98
-60.0	0.000	0.000	1.1063	0.2786	1.449	323.98
-40.0	0.000	0.000	1.1063	0.2786	1.449	323.98
-20.0	0.000	0.000	1.1063	0.2786	1.449	323.98
0.0	0.000	0.000	1.1063	0.2786	1.449	323.98

Table VI-11: Output File RFLOW.PLT for Example 3

MIT CODE PLOT FILE RHEAT.PLT: HEAT TRANSFER DATA

CRANK ANGLE (DEG)	CHAMBER GAS TEMPERATURE (K)	HEAT TRANS VELOCITY (CM/SEC)	HEAT TRANS COEFFICIENT (W/M**2 K)	COOLING TOTAL QDOT (W)	HEAT FLUX TO ROTOR (KW/M**2)	HEAT FLUX TO SIDES (KW/M**2)	HEAT FLUX TO TROCHOID (KW/M**2)
459.9	825.41	1786.78	84.9129	28.548	31.52	39.84	34.74
-620.1	825.41	1786.78	84.9129	28.548	31.52	39.84	34.74
-600.0	732.44	1786.78	90.9578	22.190	25.44	35.15	29.11
-580.0	588.48	1786.78	105.6006	12.989	14.34	26.19	18.71
-560.0	478.63	1786.78	118.3295	4.521	3.07	16.96	8.10
-540.0	406.06	1786.78	128.5730	-1.879	-6.00	9.66	-0.36
-521.0	369.13	1786.78	135.0296	-5.370	-11.29	5.69	-4.87
-520.0	368.01	1786.78	135.3559	-5.475	-11.47	5.58	-4.99
-500.0	358.37	1786.78	143.1357	-6.394	-13.50	5.07	-5.73
-480.0	350.66	1786.78	143.5075	-6.573	-14.65	4.49	-5.26
-460.0	343.00	1786.78	142.5751	-6.589	-15.64	3.86	-4.46
-440.0	336.94	1786.78	141.2360	-6.820	-16.35	3.16	-4.42
-420.0	332.42	1786.78	139.9926	-6.934	-16.84	2.68	-4.24
-400.0	329.18	1786.78	139.2168	-6.829	-17.20	2.47	-3.72
-380.0	327.04	1786.78	139.1330	-6.730	-17.49	2.36	-3.34
-360.0	325.91	1786.78	139.8522	-6.825	-17.73	2.27	-3.42
-340.0	327.14	1786.78	141.6839	-6.707	-17.79	2.42	-3.35
-320.0	331.64	1786.78	144.0286	-6.145	-17.44	2.96	-2.98
-300.0	335.09	1786.78	146.4310	-6.154	-17.22	3.14	-3.40
-280.0	337.86	1786.78	149.0824	-6.500	-17.12	3.14	-4.23
-260.1	340.29	1786.78	151.4622	-7.802	-17.03	2.53	-6.40
-256.7	340.73	1786.78	151.8660	-8.036	-17.01	2.42	-6.79
-240.0	343.59	1786.78	154.4981	-9.082	-16.86	1.87	-8.54
-240.0	343.59	1786.78	154.4981	-9.082	-16.86	1.87	-8.54
-240.0	343.59	1786.78	154.4981	-9.082	-16.86	1.87	-8.54
-240.0	343.61	1786.78	154.5224	-9.079	-16.86	1.87	-8.54
-220.0	350.49	1786.78	161.0847	-9.601	-16.47	0.82	-9.04
-200.0	361.06	1786.78	171.4574	-10.492	-15.72	-2.20	-9.13
-180.0	375.87	1786.78	186.5358	-12.698	-14.34	-11.16	-8.61
-160.0	395.61	1786.78	207.7107	-15.268	-11.86	-26.34	-7.36
-140.0	421.18	1786.78	237.0965	-17.391	-7.48	-50.33	-4.78
-120.0	453.53	1786.78	277.8181	-14.934	0.23	-75.11	1.04
-100.0	494.14	1786.78	334.1625	-6.960	13.84	-104.11	12.25
-80.0	544.73	1786.78	411.8044	11.516	37.89	-124.06	34.23
-60.0	604.07	1786.78	518.8476	41.764	78.53	-143.25	72.05
-40.0	667.43	1786.78	650.8405	86.329	139.74	-150.84	130.24
-20.0	721.25	1786.78	776.5165	134.702	208.52	-151.36	195.72
-10.0	737.57	1786.78	816.4625	151.327	232.57	-150.85	218.56
0.0	944.01	2014.09	971.9026	324.920	477.49	15.08	460.15
10.0	1471.77	2716.88	1411.7256	1011.792	1438.62	758.28	1412.48
20.0	2056.19	3514.02	1891.2009	2169.336	3032.50	2112.56	2996.72
30.0	2168.12	3699.73	1919.9226	2382.785	3293.43	2350.85	3256.33
40.0	2126.44	3688.94	1736.2036	2129.738	2905.93	2045.71	2871.67
50.0	2047.07	3631.06	1518.9747	1802.055	2421.78	1662.74	2391.31
60.0	1960.86	3563.46	1320.8676	1507.950	1992.05	1326.93	1965.28
70.0	1877.32	3496.54	1151.0283	1264.529	1639.76	1055.73	1616.19
80.0	1799.59	3433.45	1008.1429	1067.658	1357.84	842.43	1336.98
90.0	1728.57	3375.15	888.7454	909.399	1133.91	676.01	1115.44
100.0	1664.31	3321.80	789.1946	782.071	956.18	546.41	939.73
110.0	1606.47	3273.27	706.1756	679.225	814.75	445.26	799.98
120.0	1554.57	3229.29	636.8366	595.691	701.70	365.88	688.36
130.0	1508.01	3189.41	578.7661	527.335	610.77	303.01	598.71
140.0	1466.24	3153.17	529.9766	470.968	537.14	252.99	526.16
150.0	1428.93	3120.53	488.9498	424.328	477.32	213.00	467.25

Table VI-12: Output File RHEAT.PLT for Example 3

160.0	1395.59	3090.98	454.3484	386.694	428.39	184.41	419.47
170.0	1365.91	3064.37	425.1603	356.233	388.25	163.64	380.54
180.0	1339.58	3040.48	400.5555	331.009	355.24	147.12	348.57
190.0	1316.36	3019.10	379.8651	310.196	328.07	134.11	322.32
199.0	1297.90	3001.84	364.1421	298.727	307.77	134.55	303.51
200.0	1296.23	1786.78	239.5863	196.748	202.09	89.05	199.38
220.0	1245.94	1786.78	213.7977	174.322	169.59	85.29	168.80
240.0	1175.49	1786.78	180.1865	141.284	130.23	75.43	130.98
260.0	1105.66	1786.78	150.7933	112.943	98.46	66.99	100.27
280.0	1048.03	1786.78	128.8168	91.034	76.69	58.10	78.90
300.0	1000.37	1786.78	113.2030	75.525	62.00	52.33	64.47
320.0	961.17	1786.78	102.6467	63.929	52.19	47.57	54.77
340.0	929.20	1786.78	95.4316	55.370	45.47	44.72	48.16
360.0	903.22	1786.78	90.8972	48.807	40.95	42.91	43.75
380.0	881.56	1786.78	88.8613	43.852	38.11	42.21	41.04
400.0	868.66	1786.78	88.4524	40.323	36.79	42.61	39.89
420.0	856.07	1786.78	88.0504	36.674	35.52	42.54	38.74
440.0	840.43	1786.78	87.0595	32.684	33.75	41.70	37.06
459.9	820.48	1786.78	85.1293	28.428	31.31	39.76	34.64

Table VI-13: Output File RMASS.PLT for Example 3

MIT CODE PLOT FILE RMASS.PLT: MASS FRACTIONS AND EQUIVALENCE RATIO

CRANK ANGLE (deg)	PRODUCTS MASS FRACTION	UNBURNT MASS FRACTION	FUEL MASS FRACTION	EQUIVALENCE RATIO
-620.1	0.5667	0.4333	0.0352	0.5509
-600.0	0.4552	0.5448	0.0283	0.4394
-580.0	0.2827	0.7173	0.0175	0.2699
-560.0	0.1650	0.8350	0.0102	0.1563
-540.0	0.0886	0.9114	0.0055	0.0836
-521.0	0.0484	0.9516	0.0030	0.0455
-520.0	0.0470	0.9530	0.0029	0.0442
-500.0	0.0309	0.9691	0.0019	0.0291
-480.0	0.0247	0.9753	0.0015	0.0232
-460.0	0.0194	0.9806	0.0012	0.0183
-440.0	0.0156	0.9844	0.0010	0.0147
-420.0	0.0129	0.9871	0.0008	0.0121
-400.0	0.0110	0.9890	0.0007	0.0103
-380.0	0.0096	0.9904	0.0006	0.0090
-360.0	0.0085	0.9915	0.0005	0.0080
-340.0	0.0083	0.9917	0.0005	0.0078
-320.0	0.0092	0.9908	0.0006	0.0086
-300.0	0.0096	0.9904	0.0006	0.0090
-280.0	0.0098	0.9902	0.0006	0.0092
-260.1	0.0099	0.9901	0.0006	0.0093
-256.7	0.0099	0.9901	0.0006	0.0093
-240.0	0.0101	0.9899	0.0006	0.0094
-240.0	0.0101	0.9899	0.0006	0.0094
-240.0	0.0101	0.9899	0.0006	0.0094
-220.0	0.0102	0.9898	0.0006	0.0096
-200.0	0.0103	0.9897	0.0006	0.0097
-180.0	0.0105	0.9895	0.0006	0.0098
-160.0	0.0106	0.9894	0.0007	0.0100
-140.0	0.0108	0.9892	0.0007	0.0101
-120.0	0.0109	0.9891	0.0007	0.0102
-100.0	0.0109	0.9891	0.0007	0.0102
-80.0	0.0109	0.9891	0.0007	0.0102
-60.0	0.0109	0.9891	0.0007	0.0102
-40.0	0.0109	0.9891	0.0007	0.0102

-20.0	0.0109	0.9891	0.0007	0.0102
0.0	0.0742	0.9258	0.0046	0.0699
10.0	0.2636	0.7364	0.0164	0.2514
20.0	0.5166	0.4834	0.0321	0.5006
30.0	0.5987	0.4013	0.0372	0.5833
40.0	0.6186	0.3814	0.0384	0.6034
50.0	0.6230	0.3770	0.0387	0.6078
60.0	0.6235	0.3765	0.0387	0.6084
70.0	0.6232	0.3768	0.0387	0.6081
80.0	0.6229	0.3771	0.0387	0.6077
90.0	0.6225	0.3775	0.0386	0.6074
100.0	0.6223	0.3777	0.0386	0.6072
110.0	0.6222	0.3778	0.0386	0.6070
120.0	0.6222	0.3778	0.0386	0.6070
130.0	0.6222	0.3778	0.0386	0.6070
140.0	0.6222	0.3778	0.0386	0.6070
150.0	0.6222	0.3778	0.0386	0.6070
160.0	0.6222	0.3778	0.0386	0.6070
170.0	0.6222	0.3778	0.0386	0.6070
180.0	0.6222	0.3778	0.0386	0.6070
190.0	0.6222	0.3778	0.0386	0.6070
200.0	0.6222	0.3778	0.0386	0.6070
220.0	0.6222	0.3778	0.0386	0.6070
240.0	0.6222	0.3778	0.0386	0.6070
260.0	0.6219	0.3781	0.0386	0.6067
280.0	0.6213	0.3787	0.0386	0.6061
300.0	0.6202	0.3798	0.0385	0.6050
320.0	0.6182	0.3818	0.0384	0.6030
340.0	0.6149	0.3851	0.0382	0.5997
360.0	0.6101	0.3899	0.0379	0.5948
380.0	0.6011	0.3989	0.0373	0.5857
400.0	0.5913	0.4087	0.0367	0.5757
420.0	0.5825	0.4175	0.0362	0.5669
440.0	0.5744	0.4256	0.0357	0.5586
459.9	0.5664	0.4336	0.0352	0.5506

MIT CODE PLOT FILE RHOUS.PLT: TROCHOID HOUSING SURFACE TEMPERATURE

SEGMENT	CRANK ANGLE (DEG)	AVG CHAMBER TEMPERATURE (K)	AVG HOT GAS HTC (W/M2-K)	AVG COOLANT HTC (W/M2-K)	HOT SIDE WALL TEMP (K)	COOL SIDE WALL TEMP (K)	COOLANT TEMPERATURE
1	-602.1	600.19	106.95	326.02	412.51	411.57	350.00
2	-566.1	529.71	110.27	219.42	410.52	409.90	350.00
3	-530.1	473.41	114.89	138.01	408.08	407.73	350.00
4	-494.1	426.29	120.25	82.65	395.29	395.11	350.00
5	-458.1	386.24	126.19	82.65	371.93	371.85	350.00
6	-422.1	369.61	136.84	82.65	362.24	362.19	350.00
7	-386.1	350.26	142.75	82.65	350.16	350.16	350.00
8	-350.1	345.36	148.72	82.65	350.00	350.00	350.00
9	-314.1	352.63	157.34	82.65	351.72	351.72	350.00
10	-278.1	373.59	172.74	82.65	365.98	365.91	350.00
11	-242.1	416.12	201.32	82.65	396.93	396.75	350.00
12	-206.1	482.69	249.66	289.57	411.88	411.05	350.00
13	-170.1	750.47	343.36	1576.20	425.92	420.70	350.00
14	-134.1	1115.66	480.28	4053.80	444.61	429.50	350.00
15	-98.1	1322.05	595.62	6087.91	458.59	434.48	350.00
16	-62.1	1392.74	662.95	7099.60	465.41	436.59	350.00
17	-26.1	1426.04	703.44	7673.12	469.26	437.71	350.00
18	9.9	1449.81	726.58	8038.77	471.72	438.40	350.00
19	45.9	1475.32	731.94	8259.06	473.19	438.81	350.00
20	81.9	1509.26	719.91	8372.68	473.96	439.02	350.00
21	117.9	1559.26	690.43	8409.40	474.20	439.09	350.00
22	153.9	1636.91	638.77	8349.90	473.80	438.98	350.00
23	189.9	1688.32	540.45	7538.91	468.36	437.46	350.00
24	225.9	1600.92	398.16	5490.48	454.53	433.13	350.00
25	261.9	1402.51	276.88	3429.70	440.18	427.69	350.00
26	297.9	1260.02	198.91	2239.87	431.32	423.59	350.00
27	333.9	1123.79	152.50	1513.12	425.38	420.39	350.00
28	369.9	970.52	123.40	1004.62	420.71	417.53	350.00
29	405.9	815.15	109.42	668.94	417.14	415.10	350.00
30	441.9	692.70	106.04	466.41	414.61	413.23	350.00

Table VI-14: Output File RHOUS.PLT for Example 3

MIT CODE PLOT FILE RCREV.PLT: LEAKAGE AND CREVICE VOLUME DATA

CRANK ANGLE (DEG)	CHAMBER MASS (G)	LEAD CREVICE MASS (G)	LAG CREVICE MASS (G)	LEAD LEAKAGE MASS (G)	LAG LEAKAGE MASS (G)	LEAD CREVICE COMPOSITION ( )	LAG CREVICE COMPOSITION ( )
-620.1	0.1142	0.000642	0.007647	0.000000	0.000000	0.024729	0.007226
-600.0	0.1009	0.000664	0.005749	0.000107	0.001747	0.020414	0.006541
-580.0	0.1019	0.000712	0.004508	0.000218	0.003081	0.016352	0.007151
-560.0	0.1010	0.000789	0.003677	0.000364	0.004147	0.012319	0.008944
-540.0	0.1070	0.000906	0.003112	0.000562	0.005032	0.008682	0.011656
-521.0	0.1247	0.001071	0.002744	0.000803	0.005758	0.005981	0.014787
-520.0	0.1261	0.001081	0.002729	0.000817	0.005794	0.005861	0.014958
-500.0	0.1671	0.001343	0.002311	0.001133	0.006458	0.003889	0.017122
-480.0	0.2188	0.001738	0.001803	0.001533	0.006998	0.002589	0.017416
-460.0	0.2844	0.002345	0.001392	0.002062	0.007412	0.001771	0.017496
-440.0	0.3606	0.003295	0.001119	0.002793	0.007739	0.001281	0.018387
-420.0	0.4436	0.004745	0.000932	0.003835	0.008005	0.001004	0.019909
-400.0	0.5307	0.006766	0.000805	0.005333	0.008222	0.000858	0.021760
-380.0	0.6191	0.008910	0.000720	0.007398	0.008400	0.000787	0.023668
-360.0	0.7062	0.012522	0.000667	0.010022	0.008544	0.001309	0.025445
-340.0	0.7908	0.024920	0.000640	0.015009	0.008661	0.011383	0.027014
-320.0	0.8651	0.021011	0.000632	0.021214	0.008754	0.013403	0.028266
-300.0	0.9242	0.014955	0.000624	0.025900	0.008821	0.011351	0.028997
-280.0	0.9662	0.010542	0.000630	0.029205	0.008858	0.008838	0.027613
-260.1	0.9843	0.007647	0.000646	0.031550	0.008941	0.006982	0.023757
-256.7	0.9851	0.007270	0.000649	0.031878	0.008958	0.006775	0.023040
-240.0	0.9839	0.005749	0.000668	0.033297	0.009051	0.006282	0.019558
-240.0	0.9839	0.005749	0.000668	0.033297	0.009051	0.006282	0.019558
-240.0	0.9839	0.005749	0.000668	0.033305	0.009051	0.006282	0.019538
-220.0	0.9850	0.004508	0.000716	0.034638	0.009165	0.006897	0.015603
-200.0	0.9859	0.003677	0.000794	0.035704	0.009314	0.008704	0.011738
-180.0	0.9865	0.003113	0.000912	0.036590	0.009515	0.011438	0.008277
-160.0	0.9868	0.002729	0.001088	0.037352	0.009772	0.014747	0.005598
-140.0	0.9869	0.002311	0.001351	0.038015	0.010089	0.016920	0.003726
-120.0	0.9865	0.001803	0.001749	0.038469	0.010492	0.016251	0.002491
-100.0	0.9844	0.002357	0.002360	0.038885	0.011025	0.010195	0.001713
-80.0	0.9811	0.003313	0.003315	0.039618	0.011760	0.005900	0.001245
-60.0	0.9761	0.004773	0.004775	0.040666	0.012808	0.003473	0.000981
-40.0	0.9690	0.006808	0.006810	0.042174	0.014316	0.002189	0.000841
-20.0	0.9606	0.008969	0.008970	0.044251	0.016394	0.001562	0.000773
0.0	0.9518	0.012615	0.012616	0.046892	0.019036	0.001719	0.001288
10.0	0.9460	0.019158	0.019159	0.048950	0.021093	0.005334	0.005084
20.0	0.9433	0.025166	0.025167	0.051926	0.024070	0.011551	0.011384
30.0	0.9435	0.024223	0.024224	0.055206	0.027350	0.013605	0.013453
40.0	0.9447	0.021214	0.021214	0.058192	0.030335	0.013595	0.013442
50.0	0.9463	0.017996	0.017997	0.060759	0.032903	0.012784	0.012626
60.0	0.9478	0.015098	0.015099	0.062923	0.035067	0.011646	0.011482
70.0	0.9490	0.012650	0.012650	0.064737	0.036881	0.010420	0.010249
80.0	0.9500	0.010642	0.010642	0.066259	0.038403	0.009258	0.009079
90.0	0.9506	0.009016	0.009016	0.067543	0.039687	0.008265	0.008080
100.0	0.9510	0.007708	0.007708	0.068636	0.040780	0.007516	0.007327
110.0	0.9512	0.006654	0.006654	0.069575	0.041719	0.007059	0.006867
120.0	0.9513	0.005803	0.005803	0.070390	0.042534	0.006919	0.006727
130.0	0.9512	0.005113	0.005113	0.071104	0.043248	0.007100	0.006909
140.0	0.9511	0.004551	0.004551	0.071736	0.043880	0.007592	0.007404
150.0	0.9509	0.004090	0.004090	0.072302	0.044446	0.008375	0.008191
160.0	0.9506	0.003712	0.003712	0.072812	0.044956	0.009416	0.009238
170.0	0.9503	0.003400	0.003400	0.073278	0.045422	0.010679	0.010510
180.0	0.9499	0.003142	0.003142	0.073706	0.045850	0.012126	0.011965

Table VI-15: Output File RCREV.PLT for Example 3

190.0	0.9496	0.002929	0.002929	0.074103	0.046247	0.013713	0.013562
200.0	0.9491	0.002755	0.002755	0.074471	0.046616	0.015379	0.015238
220.0	0.8985	0.002333	0.002333	0.075142	0.047286	0.017536	0.017406
240.0	0.7789	0.001820	0.001820	0.075686	0.047751	0.017873	0.016881
260.0	0.6549	0.001406	0.002357	0.076105	0.048158	0.018004	0.010620
280.0	0.5551	0.001129	0.003313	0.076435	0.048892	0.018915	0.006123
300.0	0.4735	0.000941	0.004773	0.076704	0.049939	0.020433	0.003586
320.0	0.4059	0.000813	0.006808	0.076924	0.051447	0.022269	0.002246
340.0	0.3496	0.000727	0.008969	0.077105	0.053525	0.024158	0.001593
360.0	0.3018	0.000672	0.012619	0.077252	0.056167	0.025913	0.001743
380.0	0.2616	0.000644	0.025158	0.077372	0.061200	0.027458	0.011608
400.0	0.2246	0.000635	0.021214	0.077468	0.067464	0.028686	0.013610
420.0	0.1869	0.000626	0.015099	0.077538	0.072196	0.029412	0.011575
440.0	0.1497	0.000630	0.010642	0.077573	0.075532	0.028147	0.009081
459.9	0.1151	0.000646	0.007720	0.077654	0.077900	0.024254	0.007239

CRANK ANGLE (DEG)	APEX SEAL PATH LENGTH (IN)	APEX SEAL SPEED (FT/S)	PRIMARY PRESSURE (PSI)	LEAD PRESSURE (PSI)	SEAL NORMAL FORCE (LBF)	INTEGRATED FRICTION WORK (FT-LBF)	INSTANTANEOUS FRICTION FORCE (LBF)
-619.1	0.057	65.99	1.29	1.43	125.75	0.0050	8.8026
-609.1	0.639	69.53	1.29	1.45	154.96	0.0628	10.8473
-599.1	1.251	73.02	1.33	1.48	184.24	0.1362	12.8969
-589.1	1.892	76.40	1.37	1.53	213.42	0.2262	14.9395
-579.1	2.562	79.67	1.40	1.59	242.26	0.3338	16.9583
-569.1	3.259	82.78	1.39	1.67	270.43	0.4596	18.9304
-559.1	3.982	85.71	1.38	1.76	297.40	0.6040	20.8181
-549.1	4.729	88.45	1.36	1.88	322.83	0.7669	22.5980
-539.1	5.498	90.97	1.34	2.03	346.45	0.9477	24.2516
-529.1	6.287	93.26	1.32	2.20	368.03	1.1459	25.7622
-519.1	7.095	95.31	1.33	2.42	387.18	1.3601	27.1024
-509.1	7.919	97.11	1.35	2.69	403.79	1.5888	28.2650
-499.1	8.757	98.64	1.39	3.01	417.74	1.8303	29.2417
-489.1	9.607	99.90	1.39	3.41	429.37	2.0827	30.0557
-479.1	10.466	100.88	1.37	3.91	438.26	2.3440	30.6782
-469.1	11.332	101.57	1.35	4.52	444.23	2.6118	31.0961
-459.1	12.202	101.98	1.33	5.28	447.15	2.8836	31.3007
-449.1	13.074	102.10	1.32	6.24	446.88	3.1567	31.2817
-439.1	13.946	101.93	1.30	7.43	443.25	3.4284	31.0274
-429.1	14.815	101.47	1.28	8.91	436.07	3.6959	30.5246
-419.1	15.679	100.72	1.27	10.71	425.14	3.9560	29.7597
-409.1	16.535	99.69	1.26	12.84	410.31	4.2060	28.7216
-399.1	17.380	98.38	1.25	15.24	391.56	4.4430	27.4092
-389.1	18.213	96.80	1.25	17.73	369.19	4.6643	25.8431
-379.1	19.031	94.96	1.24	19.96	343.99	4.8679	24.0794
-369.1	19.832	92.87	1.25	21.55	317.19	5.0526	22.2031
-359.1	20.614	90.53	1.25	28.87	273.41	5.2144	19.1387
-349.1	21.375	87.97	1.26	43.78	204.95	5.3409	14.3468
-339.1	22.113	85.19	1.28	55.83	138.08	5.4260	9.6659
-329.1	22.826	82.23	1.30	53.00	110.98	5.4865	7.7689
-319.1	23.513	79.09	1.32	46.22	96.68	5.5359	6.7676
-309.1	24.172	75.80	1.34	39.14	85.11	5.5776	5.9580
-299.1	24.802	72.39	1.36	32.82	73.02	5.6123	5.1117
-289.1	25.403	68.90	1.38	27.50	59.50	5.6400	4.1651
-279.1	25.974	65.35	1.40	23.14	44.66	5.6605	3.1259
-269.1	26.514	61.79	1.41	19.62	29.07	5.6742	2.0347
-259.1	27.024	58.27	1.43	16.78	13.49	5.6815	0.9446
-249.1	27.505	54.85	1.45	14.50	109.10	5.6870	7.6367
-239.1	27.957	51.60	1.48	12.66	80.66	5.7164	5.6460
-229.1	28.382	48.61	1.53	11.16	56.99	5.7365	3.9890
-219.1	28.784	45.97	1.59	9.94	38.01	5.7495	2.6608
-209.1	29.165	43.78	1.67	8.95	23.55	5.7575	1.6484
-199.1	29.530	42.14	1.76	8.13	13.27	5.7620	0.9292
-189.1	29.885	41.14	1.88	7.45	6.78	5.7643	0.4747
-179.1	30.235	40.84	2.03	6.89	3.67	5.7655	0.2567
-169.1	30.585	41.27	2.20	6.43	3.62	5.7663	0.2531
-159.1	30.943	42.39	2.42	6.05	6.46	5.7675	0.4522
-149.1	31.314	44.14	2.69	5.62	11.14	5.7699	0.7797
-139.1	31.703	46.42	3.01	5.11	17.23	5.7738	1.2059
-129.1	32.113	49.13	3.41	4.55	24.85	5.7799	1.7398
-119.1	32.549	52.17	3.91	3.97	6.73	5.7846	0.4713
-109.1	33.011	55.45	4.52	3.48	27.74	5.7905	1.9420
-99.1	33.503	58.90	5.28	3.07	50.82	5.8044	3.5573
-89.1	34.024	62.43	6.24	2.75	75.13	5.8278	5.2588
-79.1	34.576	65.99	7.43	2.47	100.11	5.8622	7.0080
-69.1	35.158	69.53	8.91	2.25	125.23	5.9087	8.7662
-59.1	35.770	73.02	10.71	2.07	149.99	5.9682	10.4990
-49.1	36.412	76.40	12.84	1.91	174.06	6.0416	12.1844
-39.1	37.082	79.67	15.24	1.79	197.43	6.1293	13.8202
-29.1	37.779	82.78	17.73	1.68	220.45	6.2318	15.4314

Table VI-16: Output File RFRIC.PLT for Example 3

-19.1	38.501	85.71	19.96	1.60	243.83	6.3499	17.0683
-9.1	39.248	88.45	21.55	1.53	268.25	6.4843	18.7774
0.9	40.017	90.97	28.87	1.48	277.40	6.6326	19.4184
10.9	40.807	93.26	43.78	1.45	270.08	6.7840	18.9054
20.9	41.614	95.31	55.83	1.42	272.25	6.9355	19.0577
30.9	42.438	97.11	53.00	1.41	305.05	7.1024	21.3537
40.9	43.276	98.64	46.22	1.40	341.14	7.2931	23.8798
50.9	44.126	99.90	39.14	1.40	372.54	7.5066	26.0781
60.9	44.985	100.88	32.82	1.39	397.60	7.7392	27.8321
70.9	45.851	101.57	27.50	1.37	416.41	7.9868	29.1487
80.9	46.721	101.98	23.14	1.35	429.55	8.2452	30.0684
90.9	47.594	102.10	19.62	1.32	437.66	8.5105	30.6364
100.9	48.466	101.93	16.78	1.29	441.31	8.7791	30.8918
110.9	49.335	101.47	14.50	1.29	440.78	9.0476	30.8543
120.9	50.199	100.72	12.66	1.33	436.30	9.3128	30.5411
130.9	51.054	99.69	11.16	1.37	428.39	9.5717	29.9874
140.9	51.900	98.38	9.94	1.40	417.46	9.8218	29.2220
150.9	52.733	96.80	8.95	1.39	403.80	10.0610	28.2657
160.9	53.551	94.96	8.13	1.38	387.48	10.2872	27.1233
170.9	54.352	92.87	7.45	1.36	368.67	10.4988	25.8068
180.9	55.134	90.53	6.89	1.34	347.58	10.6944	24.3306
190.9	55.895	87.97	6.43	1.32	324.42	10.8728	22.7092
200.9	56.632	85.19	6.05	1.33	299.19	11.0333	20.9435
210.9	57.345	82.23	5.62	1.35	272.02	11.1753	19.0416
220.9	58.032	79.09	5.11	1.39	243.14	11.2986	17.0196
230.9	58.691	75.80	4.55	1.39	213.53	11.4033	14.9470
240.9	59.322	72.39	3.97	1.37	183.34	11.4903	12.8340
250.9	59.923	68.90	3.48	1.35	153.16	11.5604	10.7209
260.9	60.493	65.35	3.07	1.33	123.57	11.6151	8.6498
270.9	61.034	61.79	2.75	1.32	95.13	11.6560	6.6594
280.9	61.544	58.27	2.47	1.30	68.43	11.6847	4.7901
290.9	62.024	54.85	2.25	1.28	44.03	11.7031	3.0818
300.9	62.476	51.60	2.07	1.27	22.44	11.7133	1.5708
310.9	62.902	48.61	1.91	1.26	4.09	11.7169	0.2861
320.9	63.303	45.97	1.79	1.25	1.49	11.7185	0.1046
330.9	63.685	43.78	1.68	1.25	0.00	11.7185	0.0000
340.9	64.050	42.14	1.60	1.24	0.00	11.7185	0.0000
350.9	64.405	41.14	1.53	1.25	0.00	11.7185	0.0000
360.9	64.754	40.84	1.48	1.25	0.00	11.7185	0.0000
370.9	65.105	41.27	1.45	1.26	0.00	11.7185	0.0000
380.9	65.463	42.39	1.42	1.28	0.00	11.7185	0.0000
390.9	65.834	44.14	1.41	1.30	0.00	11.7185	0.0000
400.9	66.223	46.42	1.40	1.32	0.00	11.7185	0.0000
410.9	66.633	49.13	1.40	1.34	5.49	11.7197	0.3846
420.9	67.068	52.17	1.39	1.36	24.06	11.7244	1.6840
430.9	67.531	55.45	1.37	1.38	45.80	11.7360	3.2058
440.9	68.022	58.90	1.35	1.40	70.44	11.7564	4.9309
450.9	68.544	62.43	1.32	1.41	97.29	11.7875	6.8105

>>>> OUTPUT FROM MIT FRICTION ROUTINE

ENGINE SPEED	=	6500.0 RPM
TROCHOID CIRCUMFERENCE	=	69.04 CM
	=	27.18 IN
FRICTION WORK PER CYCLE	=	11.826 J
	=	8.722 FT-LB
AVERAGE FRICTION TORQUE	=	1.475 N-M
	=	1.088 FT-LB
FRICTION HORSEPOWER	=	0.427 KW
	=	0.572 HP

>>>> SIDE SEAL FRICTION INPUTS AND GEOMETRY

```
ENGINE ECCENTRICITY       =   0.01500 M
ROTOR RADIUS              =   0.10500 M
SIDE SEAL BASE WIDTH      =   0.00180 M
COEFFICIENT OF FRICTION   =     0.070 (-)
SPRING FORCE CONSTANT     =     75.00 N
SEAL ARC RADIUS           =    0.1950 M
SEAL SUBTENDED ARC ANGLE  =     27.80 DEG
SEAL LENGTH               =    0.1892 M

CRANK    SIDE SEAL     INSTANTANEOUS      INSTANTANEOUS
ANGLE    POSITION       NORMAL  FORCE    FRICTION FORCE
--------------------------------------------------------
--------------------------------------------------------

>>> SUMMARY: SIDE SEAL FRICTION LOSSES FOR ONE SEAL

    SEAL CENTER DISTANCE TRAVELLED =      8.051 CM

    FRICTION WORK  =      0.345 J/CYCLE
    FRICTION POWER =     0.2907 KW
                         0.3897 HP

>>> OIL RINGS

WORK AGAINST OIL SEAL FRICTION PER CYCLE (J)  =   5.41E+00
SINGLE OIL SEAL FRICTION POWER (KW)           =   1.95E-01
SINGLE OIL SEAL FRICTION POWER (HP)           =   2.62E-01
AVG NORMAL FORCE (N)                          =   1.37E+02
AVG FRICTION FORCE (N)                        =   8.20E+00

>>>> OUTPUT FROM FRICTION DRIVER ROUTINE

    FRICTION POWER FOR ALL SEALS AND BEARINGS (KW) =      5.316
    FRICTION POWER FOR ALL SEALS AND BEARINGS (HP) =      7.126
    FRICTION MEAN EFFECTIVE PRESSURE (ATM)         =      0.839
```

***** OUTPUT PLOT FILE RSIDE.PLT *****

SEGMENT	CRANK ANGLE (DEG)	AVERAGE CHAMBER TEMP (K)	AVERAGE CHAMBER HTC (W/M2-K)	OLD HOT GAS SURF TEMP (K)	NEW HOT GAS SURF TEMP (K)	OLD COOL SURFACE TEMP (K)	OLD COOL SURFACE TEMP (K)	NEW COOL HTC (W/M2-K)	COOLANT TEMPERATURE (K)
1	-602.1	600.19	1.07E+02	346.56	346.49	345.29	345.22	6.00E+02	300.0
2	-566.1	529.71	1.10E+02	336.66	336.51	335.66	335.51	6.00E+02	300.0
3	-530.1	473.41	1.15E+02	328.73	328.52	327.95	327.74	6.00E+02	300.0
4	-494.1	426.29	1.20E+02	321.82	321.58	321.23	320.99	6.00E+02	300.0
5	-458.1	386.24	1.26E+02	315.60	315.33	315.17	314.91	6.00E+02	300.0
6	-422.1	369.61	1.37E+02	313.50	313.22	313.13	312.86	6.00E+02	300.0
7	-386.1	350.26	1.43E+02	310.16	309.88	309.88	309.61	6.00E+02	300.0
8	-350.1	345.36	1.49E+02	309.48	309.21	309.22	308.96	6.00E+02	300.0
9	-314.1	352.63	1.57E+02	311.44	311.18	311.13	310.87	6.00E+02	300.0
10	-278.1	373.59	1.73E+02	317.07	316.81	316.60	316.35	6.00E+02	300.0
11	-242.1	416.12	2.01E+02	330.06	329.78	329.24	328.97	6.00E+02	300.0
12	-206.1	482.69	2.50E+02	355.04	354.74	353.53	353.24	6.00E+02	300.0
13	-170.1	750.47	3.43E+02	466.33	466.87	461.78	462.30	6.00E+02	300.0
14	-134.1	1115.66	4.80E+02	666.23	668.23	656.21	658.16	6.00E+02	300.0
15	-98.1	1322.05	5.96E+02	813.45	816.24	799.41	802.12	6.00E+02	300.0
16	-62.1	1392.74	6.63E+02	878.17	881.16	862.35	865.26	6.00E+02	300.0
17	-26.1	1426.04	7.03E+02	912.41	915.45	895.66	898.62	6.00E+02	300.0
18	9.9	1449.81	7.27E+02	934.59	937.65	917.23	920.21	6.00E+02	300.0
19	45.9	1475.32	7.32E+02	950.84	953.93	933.04	936.04	6.00E+02	300.0
20	81.9	1509.26	7.20E+02	964.70	967.86	946.51	949.59	6.00E+02	300.0
21	117.9	1559.26	6.90E+02	979.11	982.43	960.53	963.77	6.00E+02	300.0
22	153.9	1636.91	6.39E+02	995.02	998.63	976.01	979.52	6.00E+02	300.0
23	189.9	1688.32	5.40E+02	963.68	967.52	945.53	949.26	6.00E+02	300.0
24	225.9	1600.92	3.98E+02	824.15	827.61	809.82	813.17	6.00E+02	300.0
25	261.9	1402.51	2.77E+02	652.31	654.77	642.67	645.06	6.00E+02	300.0
26	297.9	1260.02	1.99E+02	542.36	544.03	535.73	537.36	6.00E+02	300.0
27	333.9	1123.79	1.53E+02	469.64	470.67	465.00	466.00	6.00E+02	300.0
28	369.9	970.52	1.23E+02	416.51	417.03	413.33	413.85	6.00E+02	300.0
29	405.9	815.15	1.09E+02	381.14	381.34	378.92	379.11	6.00E+02	300.0
30	441.9	692.70	1.06E+02	360.34	360.38	358.69	358.73	6.00E+02	300.0

Table VI-17: Output File RSIDE.PLT for Example 3

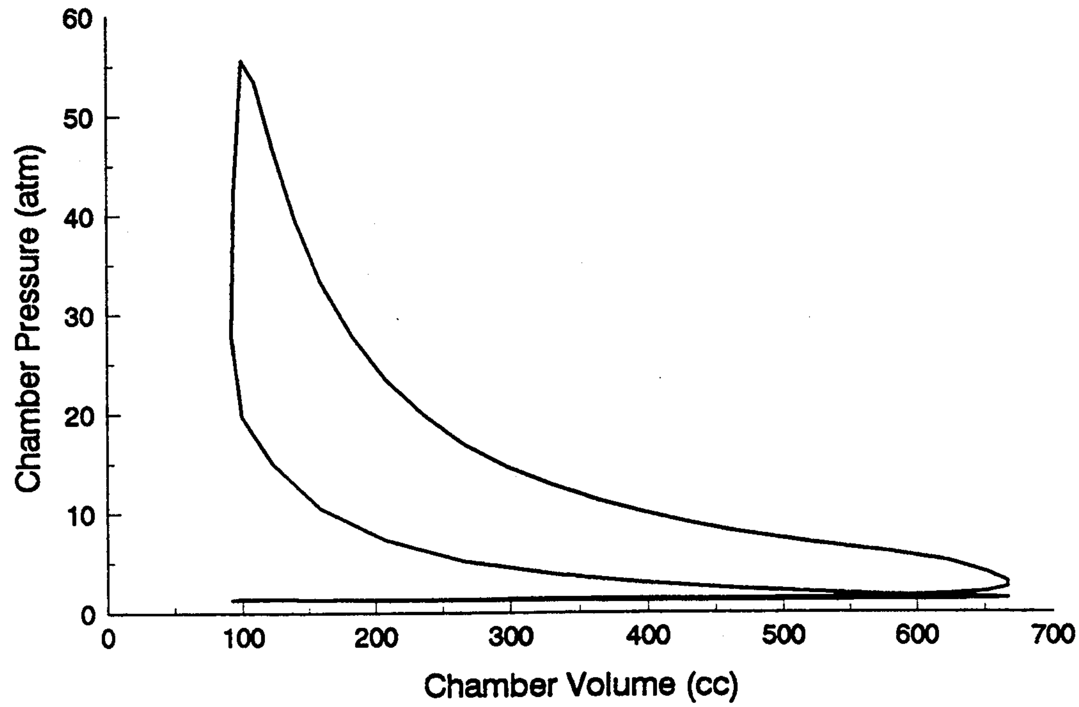


Figure VI-1: P-V Diagram

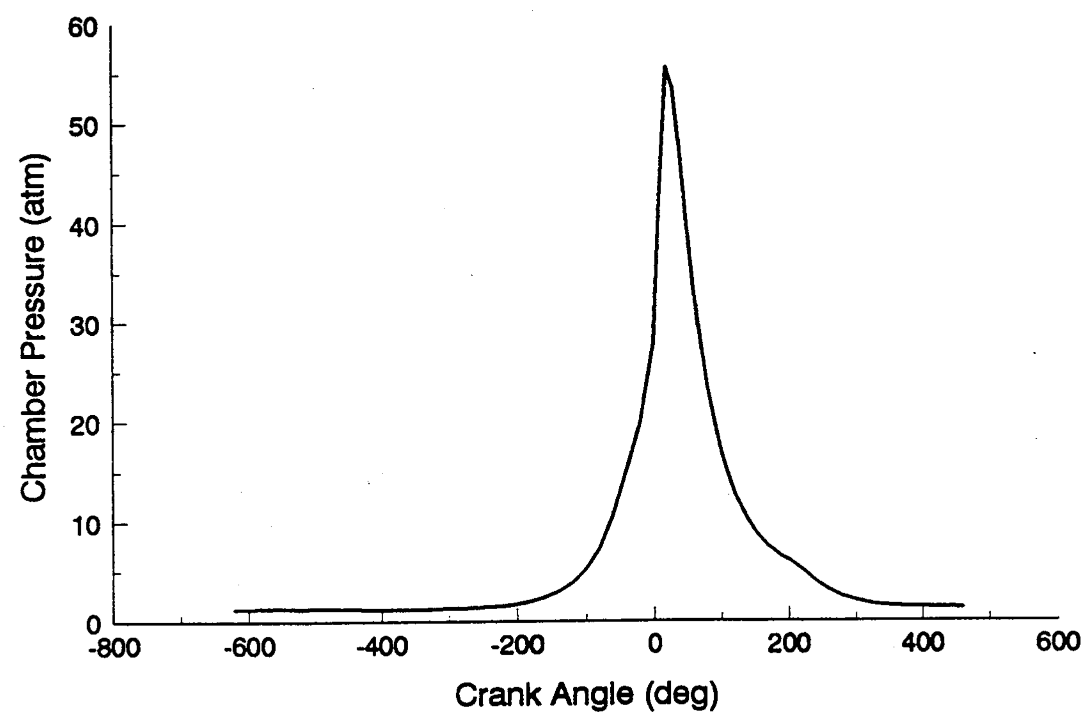


Figure VI-2: Pressure Trace

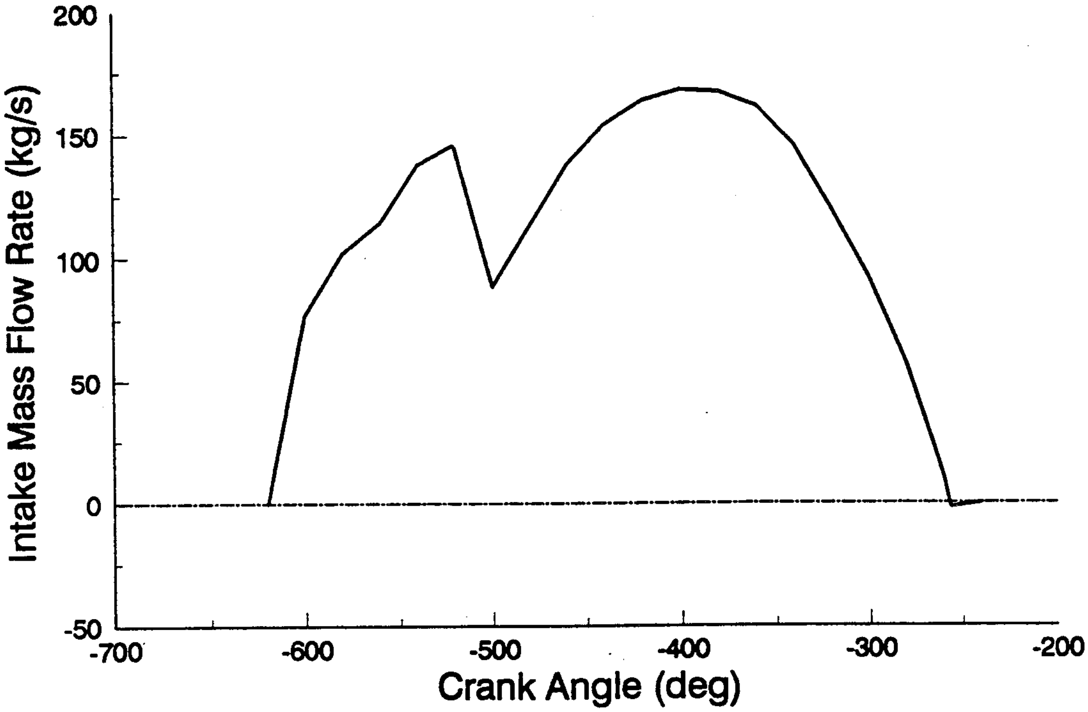


Figure VI-3: Intake Port Flow Rate

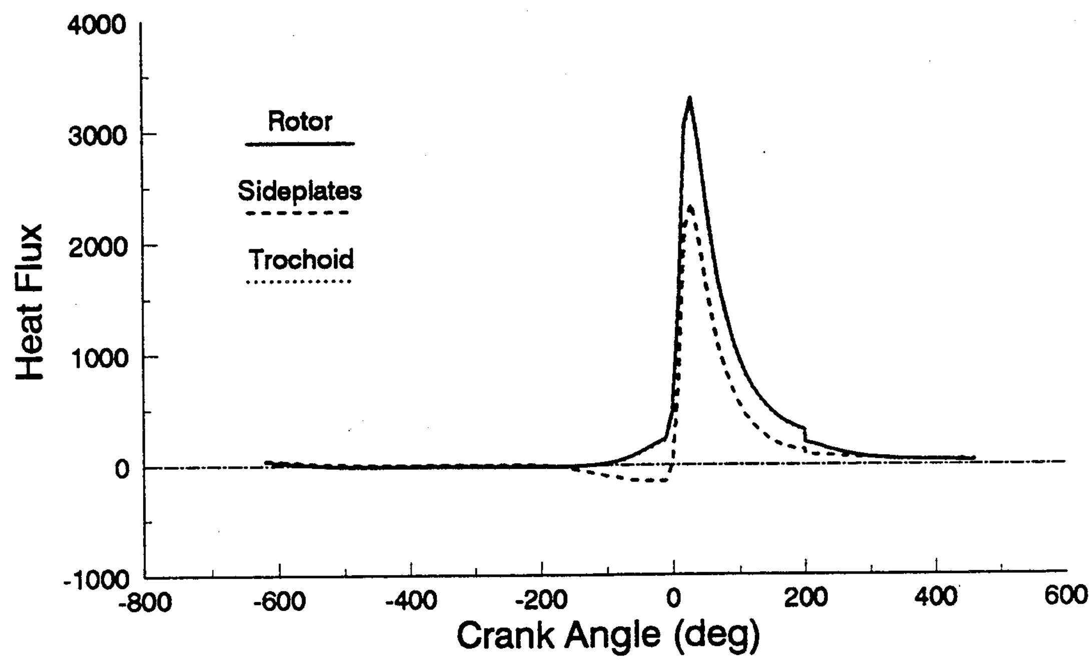


Figure VI-4: Heat Flow to the Rotor, Sideplates and Trochoid Housing

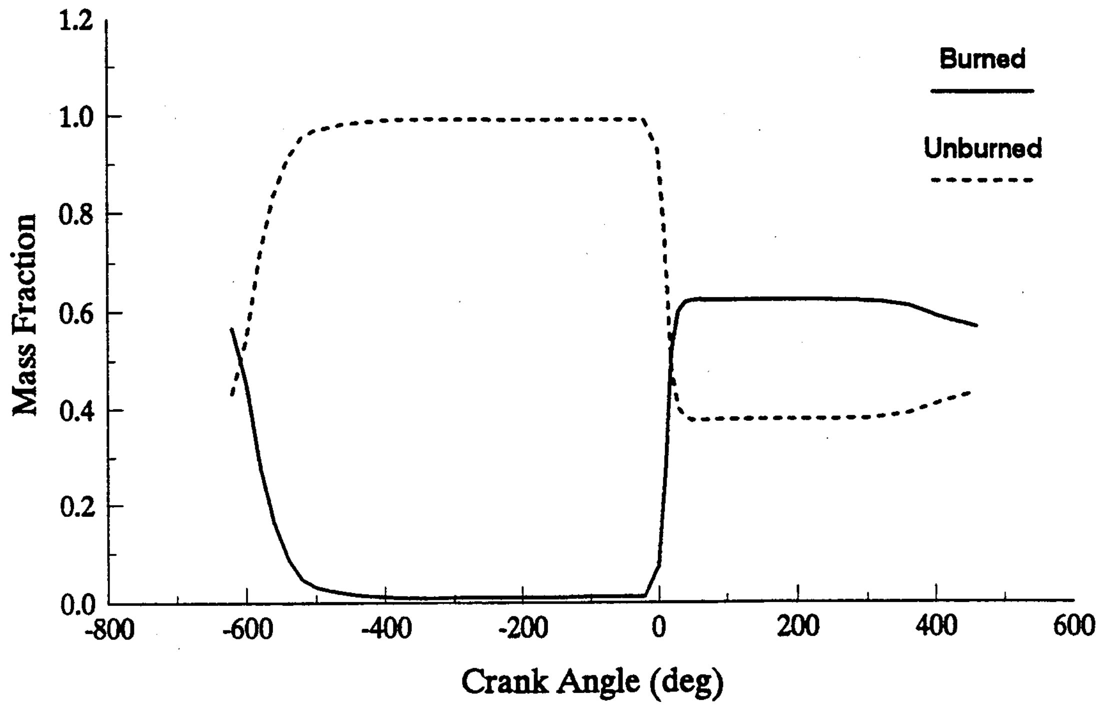


Figure VI-5: Mass Fractions v. Crank Angle

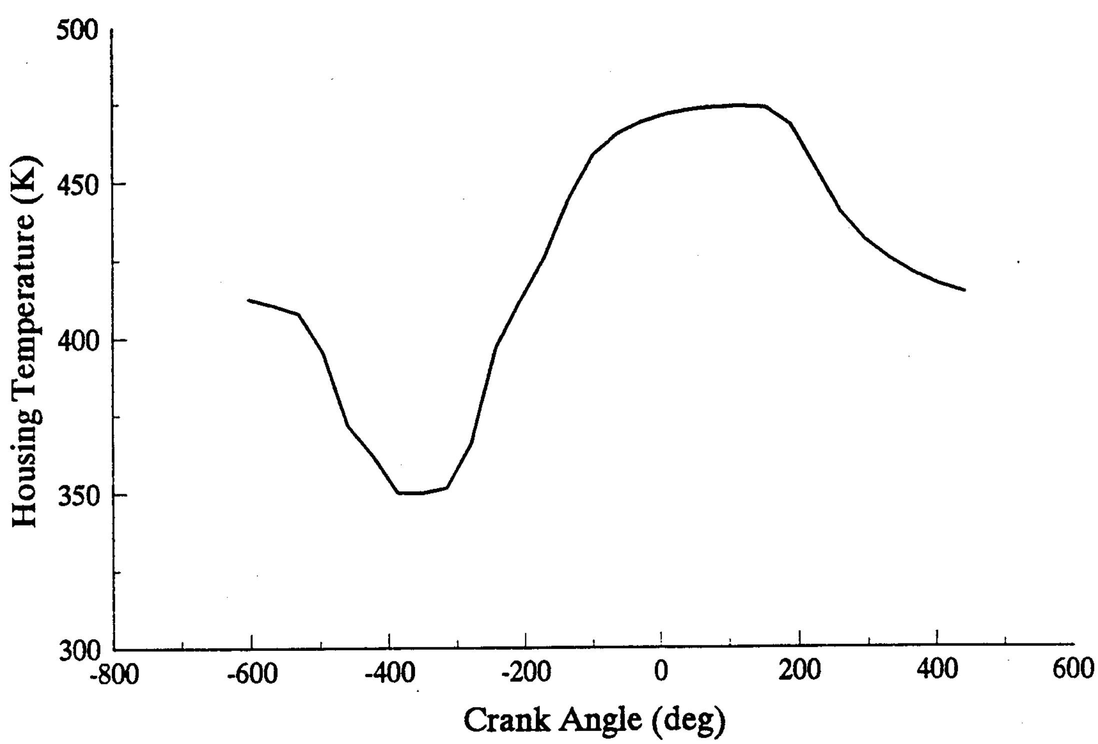


Figure VI-6: Trochoid Housing Temperature Profile

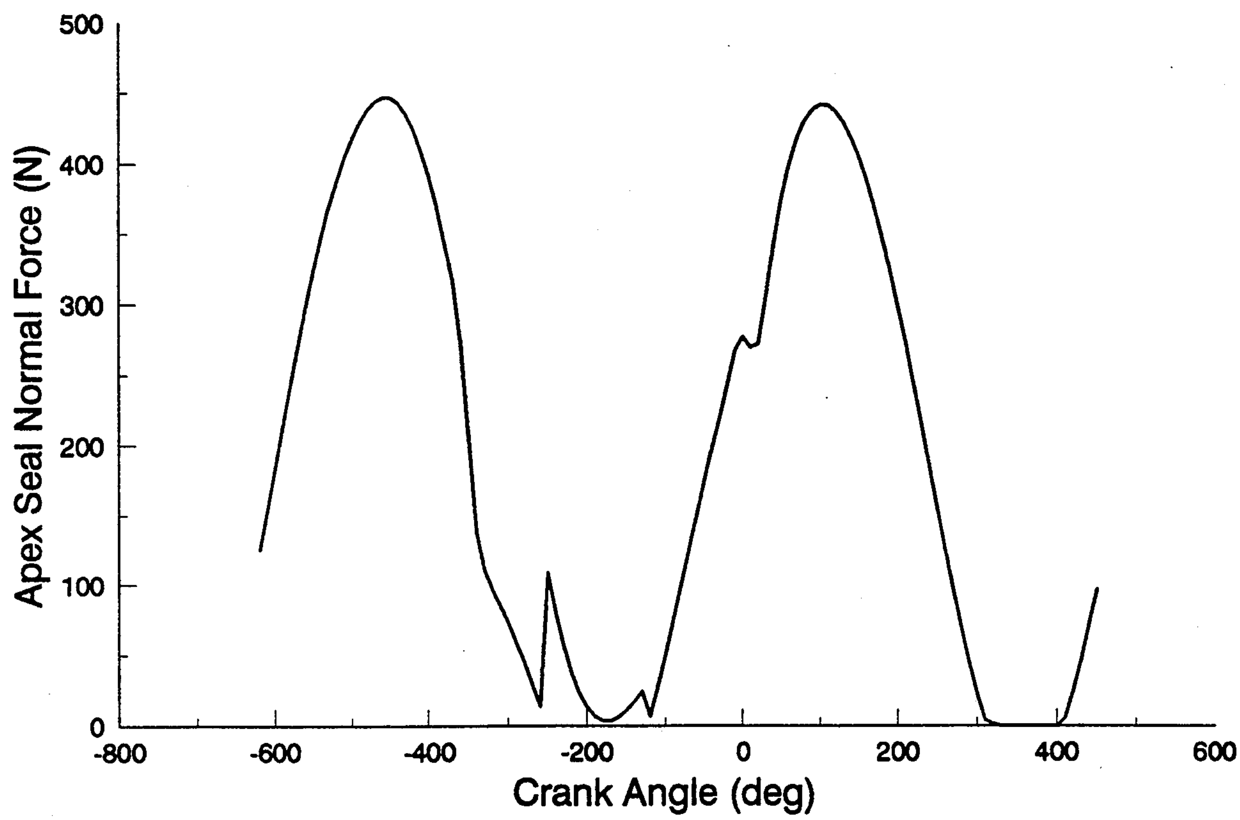


Figure VI-7: Apex Seal Normal Force During One Cycle

VII MORE EXAMPLES

Already, three examples were outlined in this guide. In section IV, single and multiple run examples were presented for a naturally aspirated engine. In section VI, inputs and results were presented for a conventionally turbocharged engine. This section includes three more examples: an engine map is generated for a supercharged engine (example 4), an engine map is generated for a conventionally turbocharged engine (example 5) and finally a two-stage-compression turbocharged engine is run from sea level to 25,000 ft (example 6). For each of these cases, the relevant inputs and outputs are discussed. CPU times are given and hints to improve code performance are offered.

VII-A A Supercharged RCE (Example 4)

The supercharged RCE model is less sophisticated than those for turbocharged engines. The user simply designates the intake and exhaust manifold pressures. No accounting is made of the work lost in running the compressor. Although it is not difficult to add provisions for use of compressor maps and to account for lost work, the authors have not yet done this.

In example 4, `RCEMAP` generated an engine map for a supercharged RCE. The input files `RCEMAP.INP` and `ROTARY.INP` are given in Tables VII-1 and VII-2. Notice that `LTCHAR`, `LPIM` and `LPEM` are all `.FALSE.` and the desired intake and exhaust manifold pressures (`PIM` and `PEM` in input file `RCEMAP.INP`) are equal to 1.7 and 1.05. Input files `HHEAT.INP`, `SHEAT.INP` and `RHEAT.INP` are all the same as in Tables VI-4 – VI-6. Also notice in Table VII-1, the engine was run from 4000 to 8000 rpm and over an equivalence ratio range from 0.4 to 0.7. No changes were made in the combustion model over these operating conditions, although it is likely, for example, that combustion proceeds differently at low load and 4000 rpm than at high load and 8000 rpm. Output file `RCEMAP.OUT` for this example is presented in Table VII-3. These results were also plotted (Figure VII-1). The computer time required for these calculations was 29:18.80 CPU minutes on a VAX 8600 mainframe computer. `RCEMAP` had no difficulty converging during this exercise.

VII-B A Conventionally Turbocharged RCE (Example 5)

`RCEMAP` generated an engine map for the conventionally turbocharged engine similar to that used in example 3 (section VI). The inputs for this example are found in Tables VI-2 – VI-6 (section VI). `RCEMAP.INP` is slightly different from Table VI-2; several engine speeds and equivalence ratios were used rather than just one. The engine map for the turbocharged engine is plotted in Figure VII-2. A comparison of Figures VII-1 and VII-2 shows that turbocharged engines consume less fuel at high power levels. The supercharged engine best fuel consumption is found in an island at medium load and speed. Fuel consumptions should not be compared, since as mentioned above, no accounting is made of the work lost to the supercharger compressor.

Sometimes it is difficult for the program to match the engine and turbocharger. The program might not converge or it returns with the message `EXECUTION HALTED AT FINDS 0001` or a similar message. Because of these difficulties, turbocharged engine cases often are run one-by-one, with the user experimenting with initial intake and exhaust manifold pressures to obtain a solution. For the case at hand, **RCEMAP** converged at low engine speeds, but not at high load and high speed conditions. This is partly because the turbomachinery was operating at high speed and performance data were sparse.

Tables VII-4 and VII-5 show turbocharged engine performance.

VII-C Two-Stage Compression Turbocharged Engine (Example 6)

The final example illustrates how **RCEMAP** models a turbocharged engine with two stages of compression. Figure 1d shows the engine configuration. The engine "flies" from sea level to 25,000 ft at a constant engine speed (7500 rpm) and constant equivalence ratio (0.7). Input file **RCEMAP.INP** is listed in Table VII-6. Table VII-7 is input file **ROTARY.INP**. Note that logical variable **L2C** equals **.T.** and namelists **ACOOL**, **ICOOL** and **NLWG** are included in **ROTARY.INP**. The turbocharger is intercooled and aftercooled and wastegated. The wastegate begins to open when the intake manifold pressure is 1.3 atm and is fully open when the intake manifold pressure is 1.9 atm (see **NLWG**).

Also note the values given to **ITABC4**, **ITABC5**, and **ITABC6** in **ROTARY.INP**. These are the table numbers for the compressor maps inside file **TURB.INP**. Table VII-8 is input file **TURB.INP**. Tables 1001 – 1003 are performance data for the high-pressure compressor (the compressor closest to the engine). These tables were made-up by the authors and do not reflect measured compressor performance data. Tables 1004 – 1006 are scaled versions of 1001 – 1003; values of corrected flow and pressure ratio from maps 1001 – 1003 were simply scaled (multiplied) by constants. The turbine maps (5001 – 5002) were also scaled from maps used for the conventionally turbocharged engine. Compressor and Turbine maps corresponding to these tables are drawn in Figures VII-3 – VII-5.

Results from example 6 are found in Table VII-9 and Figures VII-6 – VII-11. Table VII-9 is an example of output file **RSHORT.OUT** for a two-stage compression turbocharged engine. The turbocharger summary at the end of the file is different from that of the conventionally turbocharged engine, since low pressure compressor performance is included. In the **STATION TEMPERATURES AND PRESSURES** section, the temperature and pressure for each station is given. **ATM** refers to atmospheric conditions, station A is the exit of the low pressure compressor. Station AS gives the conditions at the exit of the low pressure compressor assuming isentropic compression. Station 1 is the entrance to the high pressure compressor (note the intercooler pressure drop). Station 2 is the high pressure compressor outlet. 2S is exit conditions from the high pressure compressor assuming isentropic compression. Properties at station 3 correspond to average intake manifold pressure and temperature. Properties at station 6 correspond to average exhaust manifold pressure and temperature. Station 7 is the turbine inlet and station 8 is turbine exit (atmospheric).

Low pressure compressor performance is plotted in Figure VII-6. The operating points for the compressor are plotted on compressor flow and efficiency maps. The markers show operating points from sea level to 25,000 ft at increments of 2,500 ft. The low pressure compressor runs at fairly high efficiency up to about 20,000 ft, where the speed becomes too high. Low pressure compressor corrected flow rate more than doubles. The high pressure compressor operating line is drawn on Figure VII-7. It would be preferable to redesign the compressor such that the operating line would lie closer to the middle of the map (in the high efficiency portion). The operating points for the turbine are shown in Figure VII-8. The operating line on the efficiency map is jagged because the iteration to find turbine pressure ratio and efficiency may not be sufficiently accurate. None the less, the operating line on the flow map is smooth. The turbine operating line is near the "ridge-line" connecting the peak efficiencies in the efficiency map.

Several plots were made to illustrate engine performance in example 6. Figures VII-9 and VII-10 show brake power and brake specific fuel consumption from sea level to 25,000 ft. The engine power falls slowly to about 20,000 ft. Above 20,000 ft the power lapses more rapidly with altitude. At 22,500 ft the wastegate is fully closed and the low pressure compressor is operating at higher-than-desirable speed. Like brake power, brake specific fuel consumption remains fairly constant and low to about 20,000 ft. Note that the scale on Figure VII-10 is fine and the magnitude of sfc changes is not large. Finally, the fraction of the exhaust mass passing through the wastegate is plotted in Figure VII-11.

This concludes the results section of this report. It is hoped that the preceding examples will serve as a base from which users can solve their problems of interest.

Table VII-1: `RCEMAP.INP` for Example 4

```
&RUNRCE
   NROTOR  = 1
   IFUELT  = 1
   PIM     = 1.7
   PEM     = 1.0
   NALT    = 1
   ALTL    = 0.
   ALTH    = 0.
   NRPM    = 5
   RPML    = 4000.
   RPMH    = 8000.
   NPHI    = 4
   PHIL    = 0.4
   PHIH    = 0.7
&END
```

Table VII-2: ROTARY.INP for Example 4

```
$NLCASE
   ICASE  = 3
   IDAY   = 30
   IMONTH = 9
   IYEAR  = 1991
   MAXITS = 15
$END
$NLOPCS
   LFIRE  = .T.
   LTCHAR = .F.
   L2C    = .F.
   IFUELT = 1
   EGR    = 0.0
   TEGR   = 300.
   ANCIL1 = 0.3680 ! 0.45  ! 0.5    ! 0.6
   ANCIL2 = 0.1319 ! 0.025 ! 0.0275 ! 0.03
   ANCIL3 = 0.0059
   ITABC1 = 1
   ITABC2 = 2
   ITABC3 = 3
   ITABC4 = 14
   ITABC5 = 15
   ITABC6 = 16
   ITABT1 = 4
   ITABT2 = 5
   RCORR  = 545., 13.94, 519., 14.688, 519., 14.688
$END
$NLGEOM
   ECCEN  = 1.5
   ROTRAD = 10.5
   DEPTH  = 7.
   VFLANK = 50.
   SZOVER = 0.08
   CLRNCE = 0.064
   AREALK = 0.01
   CREVOL = 0.4
$END
$NLHREL
   TSPARK = -10.
   TMAX   = 15.
   XBZERO = 0.0
   XBSTOP = 0.98
   DQDTMX = 0.05
```

```
$END
$NLPORT
   IPA    = 13.8
   EPA    = 9.
   CDIP   = 0.60
   CDEP   = 0.65
   TIPO   = -620.1
   TIPC   = -240.1
   TEPO   = 199.1
   TEPC   = 588.5
   THIPO  = 40.
   THEPO  = 40.
$END
$NLHEAT
   IHTPRO = 3.
   IRTPRO = 3.
   ISTPRO = 3.
   TROTI  = 310.
   TSIDI  = 310.
   THOUSI = 310.
   CONHT  = 0.037
   EXPHT  = 0.8
   CON1   = 0.75
   CON2   = 1.5
   LCOUET = .F.
   ALFF   = 2.0
   PRNTUR = 0.7
$END
$NLIMAN
   LPIM   = .F.
   VIM    = 2550.
   TIM    = 310.
$END
$NLEMAN
   LPEM   = .F.
   VEM    = 400.
   PEXH   = 0.95
$END
$NLWRIT
   LDEBUG = .F.,.F.,.T.,.F.,.F.,.F.,.F.,.F.,.F.,.F.,
            .F.,.F.,.F.,.F.,.F.
   LBRIEF = .T.
   TPRINT = 40.
   TPRINX = 40.
```

```
$END
$NLCONV
   TCONV  = 0.01
   PCONV  = 0.01
   XMCONV = 0.01
   TRCONV = 0.01
   THCONV = 0.01
   PMCONV = 0.01
   EMCONV = 0.01
$END
&NLAPEX
   ABASE = 0.18
   AFRC1 = 0.07
   AFRC2 = 0.13
   AHEIG = 0.77
   AMASS = 35.0
   ARAD  = 0.0813
   FSPRI = 33.36
&END
&NLSIDE
   SIDEB  = 0.18
   SIDEH  = 0.24
   SIDECF = 0.07
   SIDEF  = 75.
&END
&NLOILS
   SOILB  = 0.15
   SOILCF = 0.06
   SOILF  = 22.0
   SOILR  = 6.0
   SOILP  = 2.0
&END
&EXHFL
   EPTHIK = 0.25
   EXHPL  = 10.
   TPOUT  = 300.
   TCONP  = 24.
   EXHPEM = 0.8
   FEXHP  = 1.0
&END
&ROTORB
   NRB    = 2
   DRB    = 7.81
   WRB    = 4.50
```

```
    VRB    = 10.4
    CRB    = 0.01016
&END
&MAINB
    NMB    = 2
    DMB    = 4.60
    WMB    = 6.36
    VMB    = 10.4
    CMB    = 0.01016
&END
&ACOOL
   DPAC   = 0.03
   HAFTC  = 400.0
   TACIN  = 310.0
   AAFTC  = 0.40
&END
&ICOOL
   DPIC   = 0.03
   HINTC  = 400.0
   TICIN  = 300.0
   AINTC  = 0.40
&END
$NLWG
    PWG1   = 6002.1
    PWG2   = 6002.4
    AWG    = 0.07
    CDWG   = 0.7
&END
```

Table VII-3: RCEMAP.OUT for Example 4

```
>>>>> RCE PERFORMANCE MAP ROUTINE OUTPUT


>>>>> ENGINE PERFORMANCE PARAMETERS FOR:

      INTAKE MANIFOLD PRESSURE      =     0.0000 ATM
      INTAKE MANIFOLD TEMPERATURE =     346.981 K
      EXHAUST MANIFOLD PRESSURE     =     1.0000 ATM


   >> AIR MASS FLOW RATE (LB/HR)

PHI\RPM      4000.00     5000.00     6000.00     7000.00     8000.00
--------------------------------------------------------------------

 0.400       941.24     1081.54     1223.63     1355.90     1469.56
 0.500       929.47     1073.93     1215.87     1349.40     1466.22
 0.600       918.63     1063.75     1205.05     1340.23     1459.92
 0.700       907.58     1050.99     1192.74     1329.00     1451.61


   >> FUEL MASS FLOW RATE (LB/HR)

PHI\RPM      4000.00     5000.00     6000.00     7000.00     8000.00
--------------------------------------------------------------------

 0.400        16.48       20.76       25.10       29.21       33.10
 0.500        20.19       25.67       31.04       36.17       41.05
 0.600        23.78       30.36       36.75       42.92       48.80
 0.700        27.19       34.78       42.23       49.43       56.33


   >> BRAKE POWER (BHP)

PHI\RPM      4000.00     5000.00     6000.00     7000.00     8000.00
--------------------------------------------------------------------
```

0.400	38.19	48.77	58.60	66.80	73.30
0.500	46.97	60.70	73.65	84.80	94.19
0.600	54.70	71.50	87.27	101.40	113.67
0.700	61.47	80.76	99.41	116.35	131.38

>> HEAT TRANSFER TO COOLANT (% FUEL ENERGY)

PHI\RPM	4000.00	5000.00	6000.00	7000.00	8000.00
0.400	14.83	13.14	11.98	11.17	10.60
0.500	15.55	13.71	12.46	11.56	10.90
0.600	16.34	14.38	13.03	12.04	11.31
0.700	17.29	15.20	13.73	12.66	11.84

>> FRICTION POWER (FHP)

PHI\RPM	4000.00	5000.00	6000.00	7000.00	8000.00
0.400	9.03	12.62	17.09	22.40	28.63
0.500	9.09	12.83	17.23	22.56	28.81
0.600	9.17	12.95	17.35	22.70	28.98
0.700	9.25	13.06	17.47	22.84	29.13

>> MASS AVERAGED EXHAUST GAS TEMP (DEG R)

PHI\RPM	4000.00	5000.00	6000.00	7000.00	8000.00
0.400	1128.25	1191.40	1247.70	1299.67	1354.04
0.500	1265.25	1346.61	1413.68	1474.71	1536.82
0.600	1397.30	1494.67	1572.48	1642.44	1711.75
0.700	1523.09	1633.79	1723.05	1801.53	1877.98

>> THERMAL EFFICIENCY

PHI\RPM	4000.00	5000.00	6000.00	7000.00	8000.00
0.400	40.122	40.813	40.779	40.192	39.226
0.500	38.567	39.271	39.398	38.988	38.222
0.600	37.133	37.974	38.216	37.950	37.344
0.700	35.825	36.731	37.087	36.942	36.457

>> BRAKE SPECIFIC FUEL CONSUMPTION (LB/HP-HR)

PHI\RPM	4000.00	5000.00	6000.00	7000.00	8000.00
0.400	0.432	0.426	0.428	0.437	0.452
0.500	0.430	0.423	0.422	0.427	0.436
0.600	0.435	0.425	0.421	0.423	0.429
0.700	0.442	0.431	0.425	0.425	0.429

Table VII-4: Turbocharged Engine Brake Power (hp)

ϕ	4500 rpm	5500 rpm	6500 rpm	7500 rpm	8500 rpm
0.7	55.87	75.73	94.90	114.47	131.06
0.6	47.84	63.53	78.79	94.28	106.35
0.5	39.19	51.15	62.54	73.49	82.94
0.4	30.46	38.50	45.93	52.68	58.14

Table VII-5: Turbocharged Engine BSFC (lbm/hp-hr)

ϕ	4500 rpm	5500 rpm	6500 rpm	7500 rpm	8500 rpm
0.7	0.451	0.439	0.435	0.435	0.442
0.6	0.449	0.440	0.438	0.440	0.449
0.5	0.451	0.445	0.447	0.453	0.464
0.4	0.561	0.462	0.470	0.483	0.504

Table VII-6: `RCEMAP.INP` **for Example 6**

```
&RUNRCE
   NROTOR  = 1
   IFUELT  = 1
   PIM     = 2.0
   PEM     = 1.6
   NALT    = 11
   ALTL    = 0.
   ALTH    = 25000.
   NRPM    = 1
   RPML    = 7500.
   RPMH    = 7500.
   NPHI    = 1
   PHIL    = 0.7
   PHIH    = 0.7
&END
```

Table VII-7: ROTARY.INP for Example 6

```
$NLCASE
   ICASE=3, IDAY=30, IMONTH=9, IYEAR=1991, MAXITS=20 $END
$NLOPCS
   LFIRE=.T., LTCHAR=.T., L2C=.T., IFUELT=1, EGR=0.0, TEGR=300.,
   ANCIL1=0.3680, ANCIL2=0.1319, ANCIL3=0.0059, ITABC1=1, ITABC2=2,
   ITABC3=3, ITABC4=4, ITABC5=5, ITABC6=6, ITABT1=7, ITABT2=8,
   RCORR=545., 13.94, 519., 14.688, 519., 14.688 $END
$NLGEOM
   ECCEN=1.5, ROTRAD=10.5, DEPTH=7., VFLANK=50., SZOVER=0.08,
   CLRNCE=0.064, AREALK=0.01, CREVOL=0.4 $END
$NLHREL
   TSPARK=-10., TMAX=15., XBZERO=0.0, XBSTOP=0.98, DQDTMX=0.05 $END
$NLPORT
   IPA=13.8, EPA=9., CDIP=0.60, CDEP=0.65, TIPO=-620.1, TIPC=-240.1,
   TEPO=199.1, TEPC=588.5, THIPO=40., THEPO=40. $END
$NLHEAT
   IHTPRO=3., IRTPRO=3., ISTPRO=3., TROTI=310., TSIDI=310.,
   THOUSI=310., CONHT=0.037, EXPHT=0.8, CON1=0.75, CON2=1.5,
   LCOUET=.F., ALFF=2.0, PRNTUR=0.7 $END
$NLIMAN
   LPIM=.T., VIM=2550., TIM=310. $END
$NLEMAN
   LPEM=.T., VEM=400., PEXH=0.95 $END
$NLWRIT
   LDEBUG=.F.,.F.,.T.,.T.,.F.,.F.,.F.,.F.,.F.,.F.,.F.,.F.,.F.,.F.,.F.,
   LBRIEF=.T., TPRINT=40., TPRINX=40. $END
$NLCONV
   TCONV=0.005, PCONV=0.005, XMCONV=0.005, TRCONV=0.005, THCONV=0.005,
   PMCONV=0.005, EMCONV=0.005 $END
&NLAPEX
   ABASE=0.18, AFRC1=0.07, AFRC2=0.13, AHEIG=0.77, AMASS=35.0,
   ARAD=0.0813, FSPRI=33.36 &END
&NLSIDE
   SIDEB=0.18, SIDEH=0.24, SIDECF=0.07, SIDEF=75. &END
&NLOILS
   SOILB=0.15, SOILCF=0.06, SOILF=22.0, SOILR=6.0, SOILP=2.0 &END
&EXHFL
   EPTHIK=0.25, EXHPL=10., TPOUT=300., TCONP=24., EXHPEM=0.8,
   FEXHP=1.0 &END
&ROTORB
   NRB=2, DRB=7.81, WRB=4.50, VRB=10.4, CRB=0.01016 &END
&MAINB
   NMB=2, DMB=4.60, WMB=6.36, VMB=10.4, CMB=0.01016 &END
```

```
&ACOOL
  DPAC=0.03, HAFTC=400.0, TACIN=310.0, AAFTC=0.40 &END
&ICOOL
  DPIC=0.03, HINTC=400.0, TICIN=300.0, AINTC=0.40 &END
$NLWG
   PWG1=1.3, PWG2=1.9, AWG=0.06, CDWG=0.7 &END
```

Table VII-8: TURB.DAT for Example 6

```
 1001      COMPRESSOR FLOW MAP FOR RCEMAP USER'S GUIDE
ANGL  1        0.00
SPED  7       46.20     69.80     83.90     96.30    105.50    113.70    120.40
R     7       1.100     1.200     1.300     1.400     1.500     1.600     1.700
FLOW 7       0.0575    0.0813    0.1044    0.1286    0.1510    0.1720    0.1904
FLOW 7       0.0954    0.1285    0.1589    0.1861    0.2148    0.2426    0.2702
FLOW 7       0.1415    0.1771    0.2130    0.2460    0.2840    0.3125    0.3437
FLOW 7       0.1963    0.2304    0.2695    0.2993    0.3345    0.3633    0.3888
FLOW 7       0.2470    0.2875    0.3219    0.3499    0.3764    0.3996    0.4220
FLOW 7       0.2857    0.3191    0.3542    0.3862    0.4082    0.4278    0.4441
FLOW 7       0.3081    0.3489    0.3854    0.4165    0.4299    0.4426    0.4506
EOT
 1002      EFFICIENCY MAP FOR RCEMAP USER'S GUIDE
ANGL  1        0.00
SPED  7       46.20     69.80     83.90     96.30    105.50    113.70    120.40
R     7       1.100     1.200     1.300     1.400     1.500     1.600     1.700
EFF   7     0.56669   0.61105   0.65089   0.66913   0.69417   0.67557   0.64654
EFF   7     0.66065   0.68461   0.70845   0.71068   0.71773   0.70858   0.69463
EFF   7     0.69177   0.71628   0.72679   0.72716   0.71832   0.71052   0.69550
EFF   7     0.68888   0.72087   0.72711   0.72682   0.71131   0.69937   0.67701
EFF   7     0.65918   0.71078   0.71158   0.71142   0.69721   0.67794   0.65037
EFF   7     0.61853   0.69030   0.69362   0.68345   0.67312   0.64249   0.61891
EFF   7     0.56694   0.64447   0.65226   0.64548   0.62767   0.59396   0.56944
EOT
 1003      PRESSURE RATIO MAP FOR RCEMAP USER'S GUIDE
ANGL  1        0.00
SPED  7       46.20     69.80     83.90     96.30    105.50    113.70    120.40
R     7       1.100     1.200     1.300     1.400     1.500     1.600     1.700
PR    7      1.2864    1.2879    1.2802    1.2556    1.2341    1.2045    1.1719
PR    7      1.5558    1.5673    1.5528    1.5193    1.4798    1.4245    1.3611
PR    7      1.8213    1.8506    1.8312    1.7819    1.7128    1.6374    1.5374
PR    7      2.1426    2.1759    2.1506    2.0912    1.9853    1.8771    1.7680
PR    7      2.4758    2.4753    2.4101    2.3159    2.2078    2.0717    1.9228
PR    7      2.7959    2.7764    2.6973    2.5444    2.3934    2.2254    2.0405
PR    7      3.1396    3.0914    2.9525    2.7161    2.5132    2.2904    2.0695
EOT
 2001      SCALED COMPRESSOR FLOW MAP FOR TWO-STAGE COMPRESSION
ANGL  1        0.00
SPED  7       41.58     62.82     75.51     86.67     94.95    102.33    108.36
R     7       1.100     1.200     1.300     1.400     1.500     1.600     1.700
FLOW 7       0.0903    0.1278    0.1640    0.2021    0.2372    0.2703    0.2992
FLOW 7       0.1500    0.2019    0.2496    0.2924    0.3376    0.3813    0.4247
FLOW 7       0.2223    0.2783    0.3347    0.3866    0.4462    0.4911    0.5401
```

```
FLOW 7      0.3085   0.3621   0.4235   0.4704   0.5256   0.5708   0.6110
FLOW 7      0.3881   0.4518   0.5058   0.5498   0.5915   0.6279   0.6631
FLOW 7      0.4489   0.5014   0.5566   0.6069   0.6415   0.6723   0.6978
FLOW 7      0.4842   0.5483   0.6057   0.6545   0.6756   0.6956   0.7081
EOT
 2002       EFFICIENCY MAP FOR TWO STAGE COMPRESSION
ANGL  1       0.00
SPED  7      41.58    62.82    75.51    86.67    94.95   102.33   108.36
R     7      1.100    1.200    1.300    1.400    1.500    1.600    1.700
EFF   7    0.56669  0.61105  0.65089  0.66913  0.69417  0.67557  0.64654
EFF   7    0.66065  0.68461  0.70845  0.71068  0.71773  0.70858  0.69463
EFF   7    0.69177  0.71628  0.72679  0.72716  0.71832  0.71052  0.69550
EFF   7    0.68888  0.72087  0.72711  0.72682  0.71131  0.69937  0.67701
EFF   7    0.65918  0.71078  0.71158  0.71142  0.69721  0.67794  0.65037
EFF   7    0.61853  0.69030  0.69362  0.68345  0.67312  0.64249  0.61891
EFF   7    0.56694  0.64447  0.65226  0.64548  0.62767  0.59396  0.56944
EOT
 2003       SCALED PRESSURE RATIO MAP FOR TWO-STAGE COMPRESSION
ANGL  1       0.00
SPED  7      41.58    62.82    75.51    86.67    94.95   102.33   108.36
R     7      1.100    1.200    1.300    1.400    1.500    1.600    1.700
PR    7     1.1582   1.1570   1.1528   1.1394   1.1277   1.1115   1.0938
PR    7     1.3110   1.3094   1.3015   1.2833   1.2617   1.2315   1.1970
PR    7     1.4700   1.4640   1.4534   1.4265   1.3888   1.3477   1.2931
PR    7     1.6477   1.6414   1.6276   1.5952   1.5374   1.4784   1.4189
PR    7     1.8050   1.8047   1.7691   1.7178   1.6588   1.5846   1.5033
PR    7     1.9796   1.9689   1.9258   1.8424   1.7600   1.6684   1.5675
PR    7     2.1671   2.1408   2.0650   1.9361   1.8254   1.7039   1.5834
EOT
 5001       TURBINE CORRECTED FLOW MAP
ANGL  1       0.00
SPED  8      25.60    38.70    46.60    53.50    58.70    63.00    66.80
             70.00
PR    7     1.1659   1.1962   1.2222   1.2511   1.2912   1.3341   1.3700
FLOW 7      0.1246   0.1550   0.1857   0.2112   0.2423   0.2723   0.2992
PR    7     1.4275   1.4872   1.5595   1.6317   1.7262   1.8295   1.9562
FLOW 7      0.2835   0.3162   0.3482   0.3724   0.4056   0.4315   0.4598
PR    7     1.7838   1.8841   1.9858   2.0624   2.1769   2.3010   2.4362
FLOW 7      0.3980   0.4245   0.4451   0.4652   0.4881   0.5087   0.5305
PR    7     2.2190   2.3034   2.4709   2.5538   2.6453   2.8373   2.9379
FLOW 7      0.4725   0.4853   0.5106   0.5233   0.5336   0.5544   0.5648
PR    7     2.6060   2.7497   2.8795   2.9969   3.1464   3.2818   3.4469
FLOW 7      0.5080   0.5261   0.5392   0.5502   0.5622   0.5754   0.5822
PR    7     2.9847   3.1481   3.2920   3.4190   3.5883   3.7489   3.9139
```

```
FLOW 7        0.5307    0.5446    0.5551    0.5628    0.5728    0.5788    0.5829
PR    7       3.4180    3.5816    3.7422    3.8961    4.0665    4.2386    4.3688
FLOW 7        0.5472    0.5531    0.5613    0.5677    0.5726    0.5755    0.5759
PR    7       3.6112    3.7496    3.9076    4.0391    4.1943    4.3425    4.4809
FLOW 7        0.5353    0.5403    0.5444    0.5482    0.5502    0.5521    0.5543
EOT
 5002      TURBINE EFFICIENCY MAP
ANGL   1        0.00
SPED   8       25.60     38.70     46.60     53.50     58.70     63.00     66.80
               70.00
PR     9      1.0102    1.1356    1.1563    1.2378    1.2508    1.2797    1.3164
              1.3426    1.3719
EFF    9      0.7383    0.7583    0.7675    0.7672    0.7613    0.7376    0.6954
              0.6690    0.6391
PR     9      1.3610    1.4865    1.5042    1.6144    1.6526    1.7563    1.8034
              1.8321    1.8654
EFF    9      0.7046    0.7315    0.7381    0.7373    0.7280    0.6970    0.6805
              0.6627    0.6400
PR     9      1.6738    1.7614    1.8354    1.9083    1.9929    2.0628    2.1574
              2.2215    2.2899
EFF    9      0.6923    0.7122    0.7271    0.7315    0.7264    0.7126    0.6878
              0.6649    0.6392
PR     9      2.0745    2.1846    2.2436    2.3521    2.4607    2.5752    2.6541
              2.7083    2.7920
EFF    9      0.6863    0.7085    0.7136    0.7083    0.6972    0.6807    0.6681
              0.6516    0.6318
PR     9      2.4432    2.5762    2.6842    2.7927    2.9056    3.0197    3.1072
              3.2061    3.2808
EFF    9      0.6733    0.6905    0.6941    0.6883    0.6791    0.6704    0.6603
              0.6500    0.6397
PR     9      2.9093    3.0325    3.1166    3.2178    3.3261    3.3996    3.4899
              3.5861    3.6892
EFF    9      0.6518    0.6643    0.6723    0.6751    0.6694    0.6608    0.6495
              0.6371    0.6178
PR     9      3.3688    3.4836    3.6266    3.7319    3.8347    3.9307    4.0012
              4.0903    4.1570
EFF    9      0.6226    0.6334    0.6445    0.6455    0.6373    0.6282    0.6196
              0.6070    0.5914
PR     9      3.5450    3.7162    3.8903    4.0450    4.1703    4.2534    4.4076
              4.4046    4.4697
EFF    9      0.6048    0.6119    0.6163    0.6157    0.6102    0.6025    0.5944
              0.5845    0.5728
EOT
```

Table VII-9: An example of RSHORT.OUT for Example 6

```
>>>>>> OUTPUT FROM MIT DISC RCE PERFORMANCE MODEL

CASE  3,   30 SEP  1991



>>>>>> BRIEF ECHO OF ENGINE GEOMTERY AND OPERATING CONDITIONS

       NUMBER OF ROTORS                         =          1
       ENGINE SPEED (RPM)                       =    7500.00
       EQUIVALENCE RATIO (-)                    =      0.700
       DISPLACED VOLUME (CC)                    =     577.16
       AVERAGE INTAKE MANIFOLD PRESSURE (ATM)   =       1.57
       AVERAGE INTAKE MANIFOLD TEMPERATURE (K)  =     327.31
       EXHAUST GAS RECIRCULATION (%)            =       0.00
       AVERAGE EXHAUST MANIFOLD PRESSURE (ATM)  =       1.12
       NORMALIZED MAX COMB HEAT RELEASE RATE    =     0.0500
       ANGLE FOR MAX HEAT RELEASE RATE          =      15.00
       HEAT RELEASE RATE DECAY CONSTANT         =     7.1000
       FUEL USED IS ISOOCTANE
       INTAKE MANIFOLD PROPERTIES ARE VARIABLE



>>>>>> CONVERGENCE SUMMARY FOR ITERATION 15 OUT OF 15 ALLOWED

       CYCLE INITIAL CHAMBER PRESSURE (ATM)     =      1.393
       CHANGE IN INITIAL PRESSURE (%)           =       0.02

       CYCLE INITIAL CHAMBER TEMPERATURE (K)    =     887.70
       CHANGE IN INITIAL TEMPERATURE (%)        =      -0.02

       AVERAGE INTAKE MANIFOLD PRESSURE (ATM)   =      1.566
       CHANGE IN AVG INTAKE MAN PRESS (%)       =       0.12

       AVERAGE EXHAUST MANIFOLD PRESSURE (ATM)  =      1.369
       CHANGE IN AVG EXHAUST MAN PRESS (%)      =       0.06

       CYCLE INITIAL INT MANIFOLD PRESS (ATM)   =      1.571
       CHANGE IN INITIAL INTAKE MAN PRESS (%)   =       0.08

       CYCLE INITIAL EXH MANIFOLD PRESS (ATM)   =      0.979
       CHANGE IN INITIAL EXHAUST MAN PRESS (%)  =       0.12
```

```
CURRENT CYCLE INTAKE MASS (G)              =       1.227
CURRENT CYCLE EXHAUST MASS (G)             =       1.274
MASS LEAKED TO LEAD CREVICE (G)            =       0.001
MASS LEAKED TO LAG CREVICE (G)             =      -0.001
CYCLE MASS OF FUEL INJECTED (G)            =     0.04748
INITIAL MASS IN THE CHAMBER (G)            =       0.114
DIFF IN INTAKE AND EXHAUST MASS (%)        =        0.09

MAX TROCHOID HOUSING TEMPERATURE (K)       =      498.90
MAX CHANGE IN TROCH HOUSING TEMP (%)       =        0.02
NEW ROTOR FACE TEMPERATURE (K)             =      513.85
CHANGE IN ROTOR FACE TEMPERATURE (%)       =        0.03


>>>>> SEAL AND BEARING FRICTION


     -->  FRICTION POWER, ALL APEX SEALS (3 PER ROTOR)
                           (KW)          ---->       1.938
                           (HP)          ---->       2.599
     -->  FRICTION POWER, ALL SIDE SEALS (6 PER ROTOR)
                           (KW)          ---->       2.264
                           (HP)          ---->       3.035
     -->  FRICTION POWER, ALL OIL SEALS (2 PER ROTOR)
                           (KW)          ---->       0.451
                           (HP)          ---->       0.604
     -->  FRICTION POWER, ALL MAIN BEARINGS
                           (KW)          ---->       0.491
                           (HP)          ---->       0.658
     -->  FRICTION POWER, ALL ROTOR BEARINGS
                           (KW)          ---->       1.701
                           (HP)          ---->       2.280
     -->  FRICTION POWER FOR ANCILLARY COMPONENTS
                           (KW)          ---->      12.348
                           (HP)          ---->      16.552
     -->  FRICTION POWER FOR ALL SEALS AND BEARINGS
                           (KW)          ---->       6.845
                           (HP)          ---->       9.176
     -->  TOTAL FRICTION POWER
                           (KW)          ---->      19.193
                           (HP)          ---->      25.728
```

```
>>>>> HEAT TRANSFER


 -->  MAXIMUM TROCHOID HOUSING SURFACE TEMPERATURE
                          (K)             ---->     498.9
                          (DEG F)         ---->     438.4
      MAX SURFACE TEMP OCCURS NEAR  117.90 DEG
 -->  AVERAGE ROTOR SURFACE TEMPERATURE
                          (K)             ---->     513.9
                          (DEG F)         ---->     465.3
 -->  TEMPERATURE DROP IN THE EXHAUST MANFOLD
                          (K)             ---->       2.7
                          (DEG F)         ---->       4.8
 -->  (HEAT TRANSFER PER CYCLE)/(MASS OF FUEL TIMES LHV)
                          (%)             ---->      13.3
 -->  HEAT TRANSFER TO ROTOR FACE, ONE CYCLE
                          (KJ)            ---->    0.1208
                          (BTU)           ---->    0.1145
 -->  HEAT TRANSFER TO SIDE HOUSING, ONE CYCLE
                          (KJ)            ---->    0.0198
                          (BTU)           ---->    0.0187
 -->  HEAT TRANSFER TO TROCHOID HOUSING, ONE CYCLE
                          (KJ)            ---->    0.1408
                          (BTU)           ---->    0.1335


>>>>> CHAMBER PROPERTIES


 -->  MAXIMUM CHAMBER PRESSURE
                          (KPA)           ---->    6716.4
                          (PSI)           ---->    974.13
                          (ATM)           ---->     66.29
      MAX PRESSURE OCCURS AT   22.71 DEG
 -->  MAXIMUM CHAMBER TEMPERATURE
                          (K)             ---->    2363.0
                          (DEG F)         ---->    3793.8
      MAX TEMPERATURE OCCURS AT   30.00 DEG
 -->  MASS AVERAGED EXHAUST GAS TEMPERATURE
                          (K)             ---->    1042.8
                          (DEG F)         ---->    1417.3
 -->  TIME AVERAGED EXHAUST GAS TEMPERATURE
                          (K)             ---->     888.5
                          (DEG F)         ---->    1139.6
```

```
-->  TIME AVERAGED INTAKE MANIFOLD PRESSURE
                           (KPA)          ---->      158.7
                           (PSI)          ---->      23.02
                           (ATM)          ---->       1.57
-->  TIME AVERAGED INTAKE MANIFOLD TEMPERATURE
                           (K)            ---->     327.31
                           (DEG F)        ---->     129.49
-->  MAXIMUM INTAKE MANIFOLD PRESSURE
                           (KPA)          ---->      161.7
                           (PSI)          ---->      23.45
                           (ATM)          ---->       1.60
     MAX PRESSURE OCCURS AT -564.00 DEG
-->  TIME AVERAGED EXHAUST MANIFOLD PRESSURE
                           (KPA)          ---->      138.7
                           (PSI)          ---->      20.12
                           (ATM)          ---->       1.37
-->  TIME AVERAGED EXHAUST MANIFOLD TEMPERATURE
                           (K)            ---->     946.14
                           (DEG F)        ---->    1243.39


>>>>> MEAN EFFECTIVE PRESSURE AND POWER


-->  GROSS INDICATED MEAN EFFECTIVE PRESSURE (IMEP)
                           (KPA)          ---->     1359.1
                           (PSI)          ---->     197.13
                           (ATM)          ---->      13.41
-->  PUMPING MEAN EFFECTIVE PRESSURE (PMEP)
                           (KPA)          ---->      -44.1
                           (PSI)          ---->      -6.40
                           (ATM)          ---->      -0.44
-->  FRICTION MEAN EFFECTIVE PRESSURE (FMEP)
                           (KPA)          ---->      266.0
                           (PSI)          ---->      38.58
                           (ATM)          ---->       2.63
-->  BRAKE MEAN EFFECTIVE PRESSURE (BMEP)
                           (KPA)          ---->     1093.1
                           (PSI)          ---->     158.54
                           (ATM)          ---->      10.79
-->  INDICATED POWER, ONE ROTOR (IHP)
                           (KW)           ---->      98.05
                           (HP)           ---->     131.44
-->  FRICTION POWER, ONE ROTOR (FHP)
```

```
                         (KW)          ---->       19.19
                         (HP)          ---->       25.73
    -->  BRAKE POWER ONE ROTOR (BHP)
                         (KW)          ---->       78.86
                         (HP)          ---->      105.71


>>>>> EFFICIENCY AND FUEL CONSUMPTION


    -->  VOLUMETRIC EFFIC BASED ON INTAKE MANIFOLD PRESS
                         (%)           ---->        97.0
    -->  TRAPPING EFFICIENCY
                         (%)           ---->        85.8
    -->  GROSS INDICATED THERMAL EFFICIENCY
                         (%)           ---->        37.2
    -->  NET INDICATED THERMAL EFFICIENCY
                         (%)           ---->        36.0
    -->  GROSS INDICATED SPECIFIC FUEL CONSUMPTION (ISFC)
                         (G/IKW-HR)    ---->        218.
                         (LB/HP-HR)    ---->       0.358
    -->  BRAKE SPECIFIC FUEL CONSUMPTION (BSFC)
                         (G/IKW-HR)    ---->        271.
                         (LB/HP-HR)    ---->       0.446


>>>>> COMBUSTION


    -->  IGNITION DELAY (0 - 10%)
                         (CRANK ANGLE) ---->       10.45
                         (MS)          ---->        0.23
    -->  BURN DURATION (10 - 90%)
                         (CRANK ANGLE) ---->       25.54
                         (MS)          ---->        0.57


>>>>> MASS FLOW


    -->  MASS IN CYLINDER AT TIME INTAKE PORT OPENS
                         (G)           ---->       0.114
                         (LBM)         ---->     0.00025
    -->  MASS IN CYLINDER AT TIME INTAKE PORT CLOSES
```

```
                         (G)              ---->       1.034
                         (LBM)            ---->     0.00228
 -->  MASS THROUGH THE INTAKE PORT (ONE CHAMBER)
                         (G/CYCLE)        ---->       1.227
                         (LBM/CYCLE)      ---->     0.00271
 -->  MASS THROUGH THE EXHAUST PORT (ONE CHAMBER)
                         (G/CYCLE)        ---->       1.274
                         (LBM/CYCLE)      ---->     0.00281
 -->  MASS OF FUEL INJECTED (ONE CHAMBER)
                         (G/CYCLE)        ---->       0.047
                         (LBM/CYCLE)      ---->     0.00010
 -->  MASS LEAKED TO THE LEAD CREVICE (ONE CHAMBER)
                         (G/CYCLE)        ---->       0.001
                         (LBM/CYCLE)      ---->     0.00000
 -->  MASS LEAKED TO THE LAG CREVICE (ONE CHAMBER)
                         (G/CYCLE)        ---->      -0.001
                         (LBM/CYCLE)      ---->     0.00000
 -->  TOTAL AIR TO ALL ROTORS FOR 1 CYCLE
                         (G/CYCLE)        ---->     3.68221
                         (LBM/CYCLE)      ---->     0.00812
 -->  TOTAL AIR MASS FLOW RATE (TO ALL ROTORS)
                         (G/SEC)          ---->      153.43
                         (LBM/HR)         ---->      1217.6
 -->  TOTAL FUEL MASS FLOW RATE (TO ALL ROTORS)
                         (G/SEC)          ---->       5.935
                         (LBM/HR)         ---->        47.1
 -->  RESIDUAL FRACTION                   ---->       0.009


>>>>> WORK, HEAT TRANSFER AND POWER


 -->  HEAT TRANS TO STRUCTURE DURING COMBUST. AND EXPAN.
                         (KJ/CYCLE)       ---->       0.270
                         (BTU/CYCLE)      ---->       0.256
 -->  INDICATED SHAFT WORK DURING COMBUST. AND EXPANS.
                         (KJ/CYCLE)       ---->       0.784
                         (BTU/CYCLE)      ---->       0.744
 -->  HEAT TRANSFER TO STRUCTURE FOR ONE CHAMBER
                         (KJ/CYCLE)       ---->       0.281
                         (BTU/CYCLE)      ---->       0.267
 -->  INDICATED SHAFT WORK FOR ONE CHAMBER
                         (KJ/CYCLE)       ---->       0.759
                         (BTU/CYCLE)      ---->       0.720
```

```
--> INDICATED POWER (INCLUDING ALL ROTORS)
                    (KW)           ---->     94.873
                    (HP)           ---->    127.178

--------------------------------------------------

>>> ITERATION NUMBER  14
    SPEED CONVERGED TO WITHIN =       0.125 krpm
    ALTITUDE     =      10000. ft

>>> LOW PRESSURE COMPRESSOR OPERATING CONDITIONS
    PRESSURE RATIO  =     1.533
    MAP INTERPOLATION R  =    1.4445
    CORRECTED FLOW (lbm/min)    =     0.474
    CORRECTED SPEED (rpm/1000) =    84.158
    EFFICIENCY (%)              =    72.194
    ACTUAL MASS FLOW (lbm/hr)  =   1217.61
    POWER (hp)                  = -10.0269

>>> COMPRESSOR OPERATING CONDITIONS
    PRESSURE RATIO  =     1.560
    MAP INTERPOLATION R  =    1.6414
    CORRECTED FLOW (lbm/min)    =     0.312
    CORRECTED SPEED (rpm/1000) =    81.564
    EFFICIENCY (%)              =    70.643
    ACTUAL MASS FLOW (lbm/hr)  =   1217.61
    ACTUAL SPEED (rpm)          =   81188.5
    POWER (hp)                  = -11.9534

>>> TURBINE OPERATING CONDITIONS
    PRESSURE RATIO  =     1.877
    CORRECTED FLOW (lbm/min)     =     0.426
    CORRECTED SPEED (rpm/1000)  =    44.819
    EFFICIENCY (%)               =    73.920
    WASTEGATE FRACTION OPEN      =    0.4964
    WASTEGATE FLOW RATE (lb/hr) =      2.78
    % OF FLOW TO WASTEGATE       =    13.175
    ACTUAL MASS FLOW (lbm/hr)   =   1098.09
    ACTUAL SPEED (rpm)           =   81188.5
```

POWER (hp) = 21.8927

>>> STATION TEMPERATURES AND PRESSURES

WORK ERROR = -0.400 %

STATION	TEMPERATURE (K)	PRESSURE (ATM)
ATM	268.3	0.688
A	316.6	1.055
AS	303.2	1.055
1	300.0	1.025
2	357.3	1.598
2S	340.5	1.598
3	327.3	1.566
6	946.1	1.369
7	946.1	1.296
8	848.2	0.688
8S	813.7	0.688

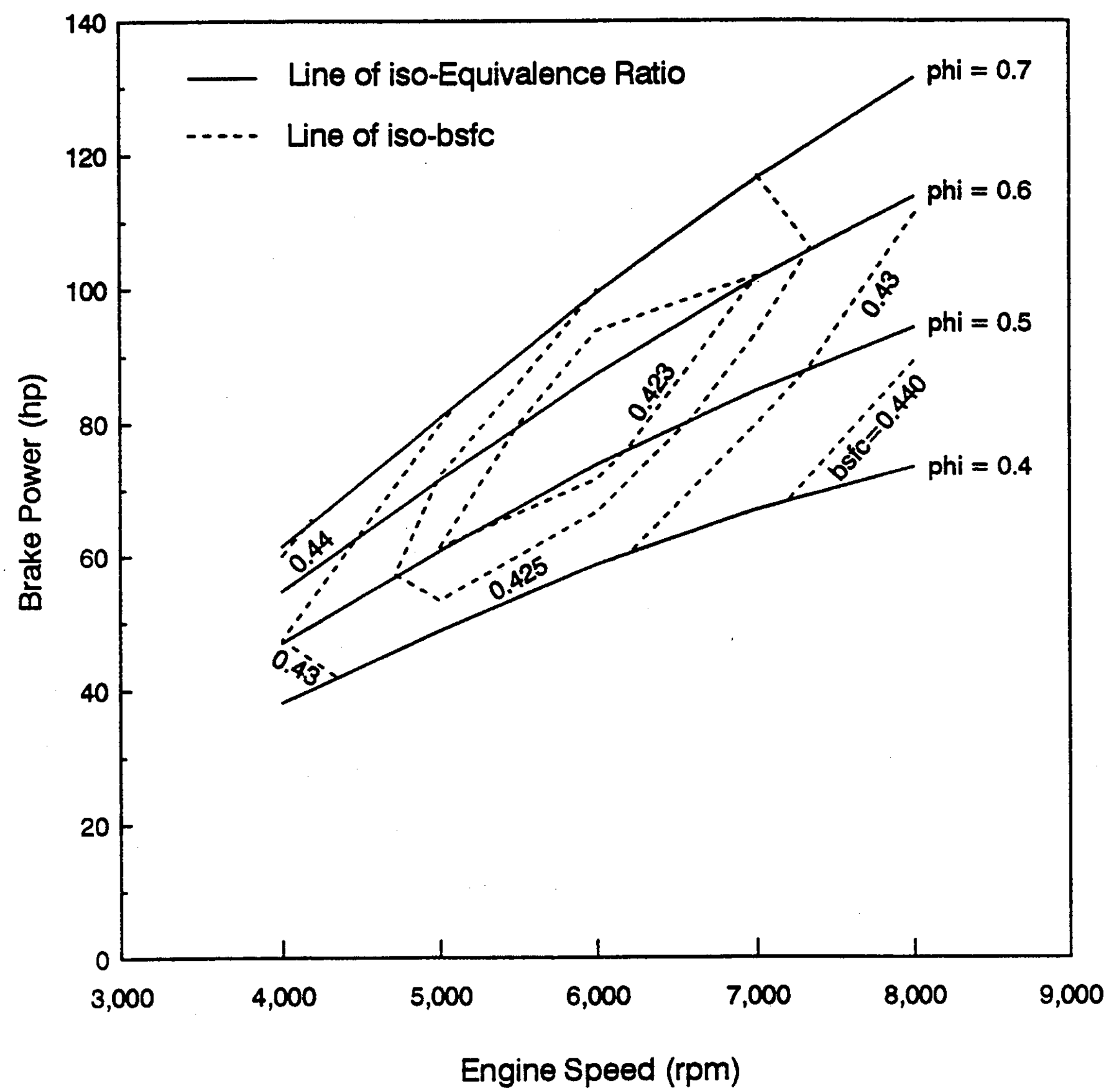


Figure VII-1: Supercharged Engine Map

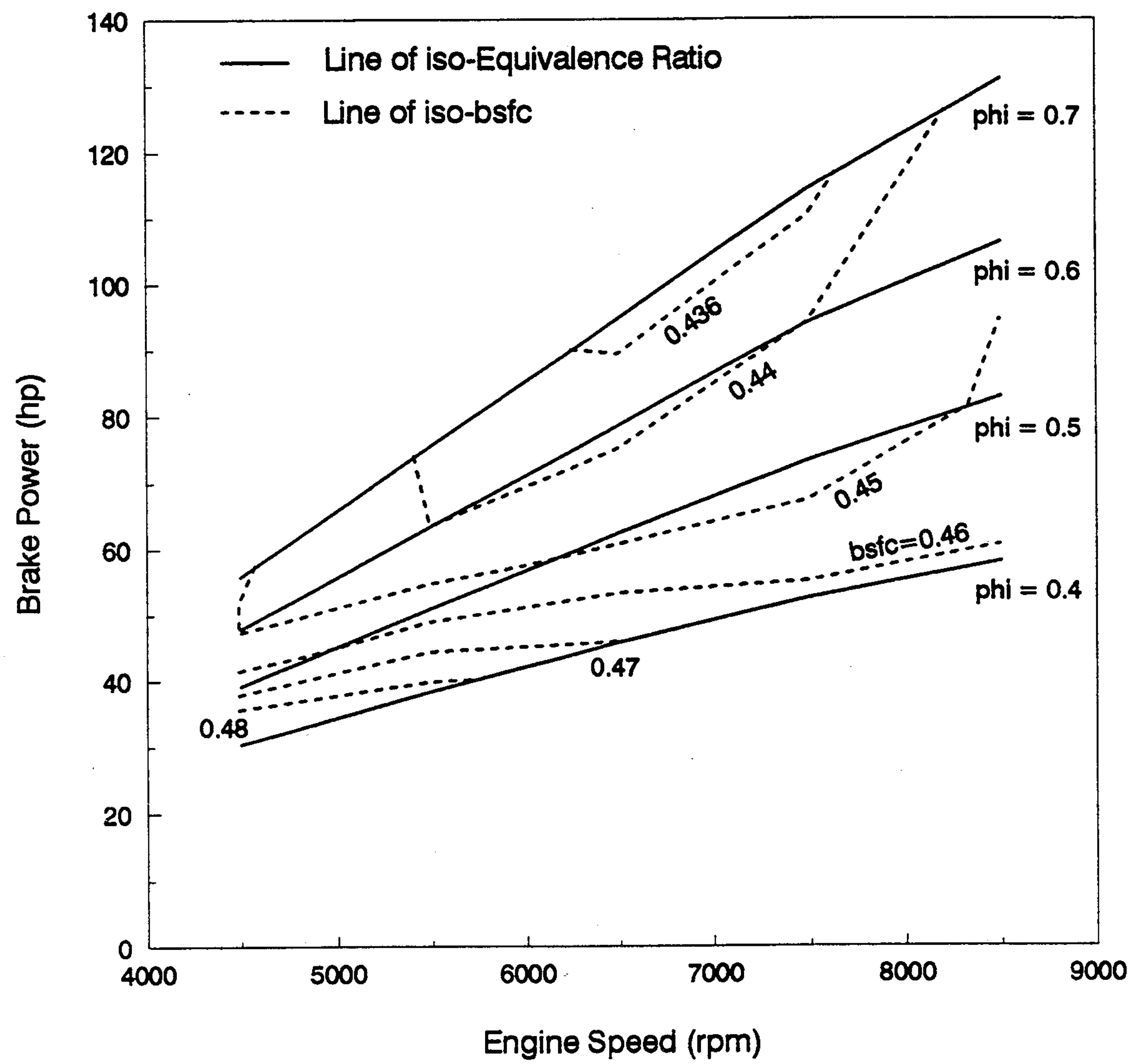
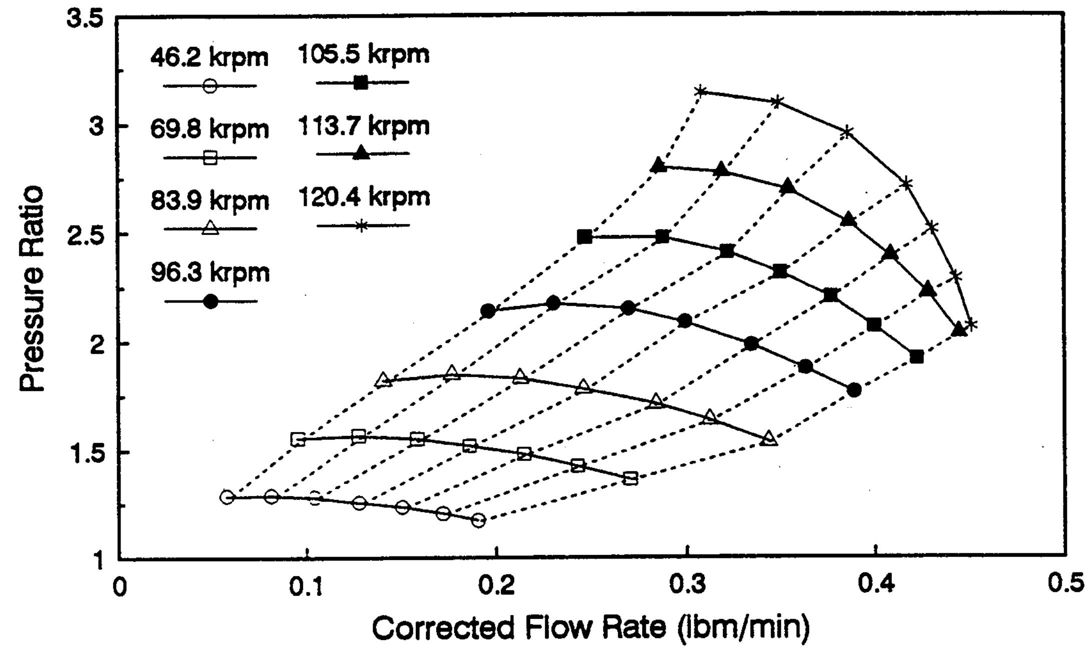
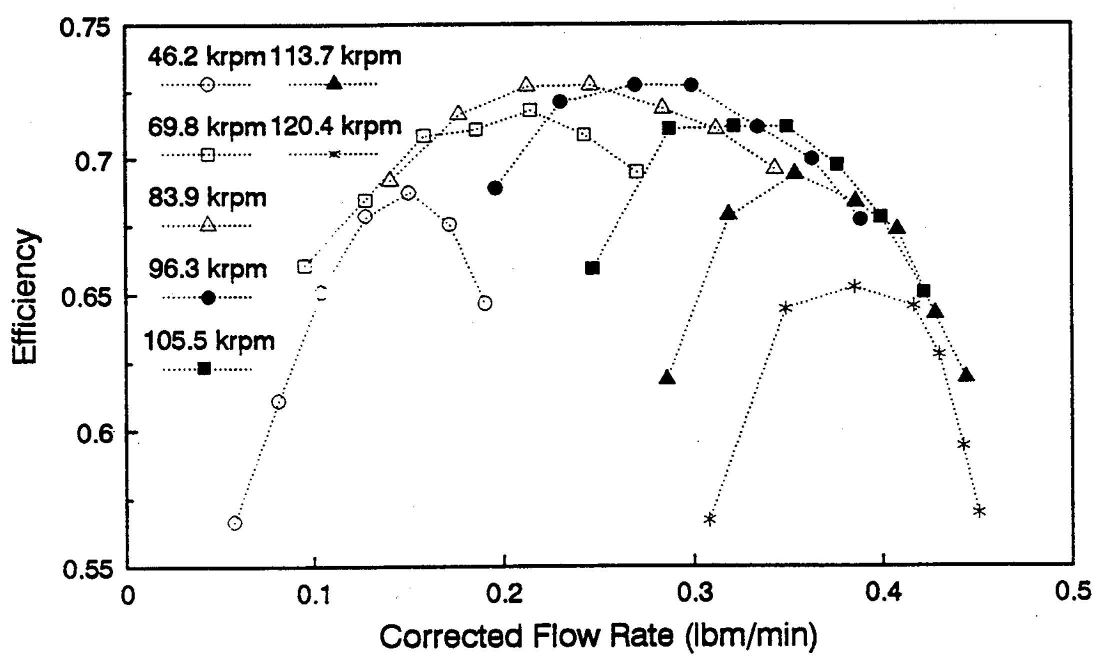


Figure VII-2: Turbocharged Engine Map

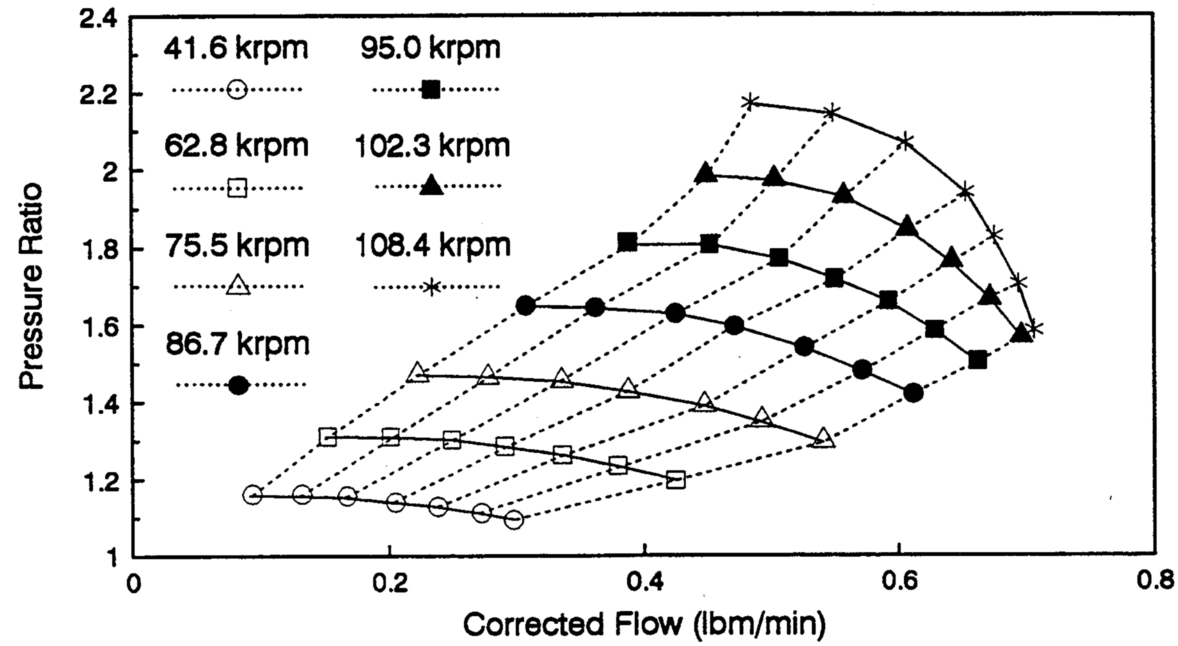


(a) Flow Map

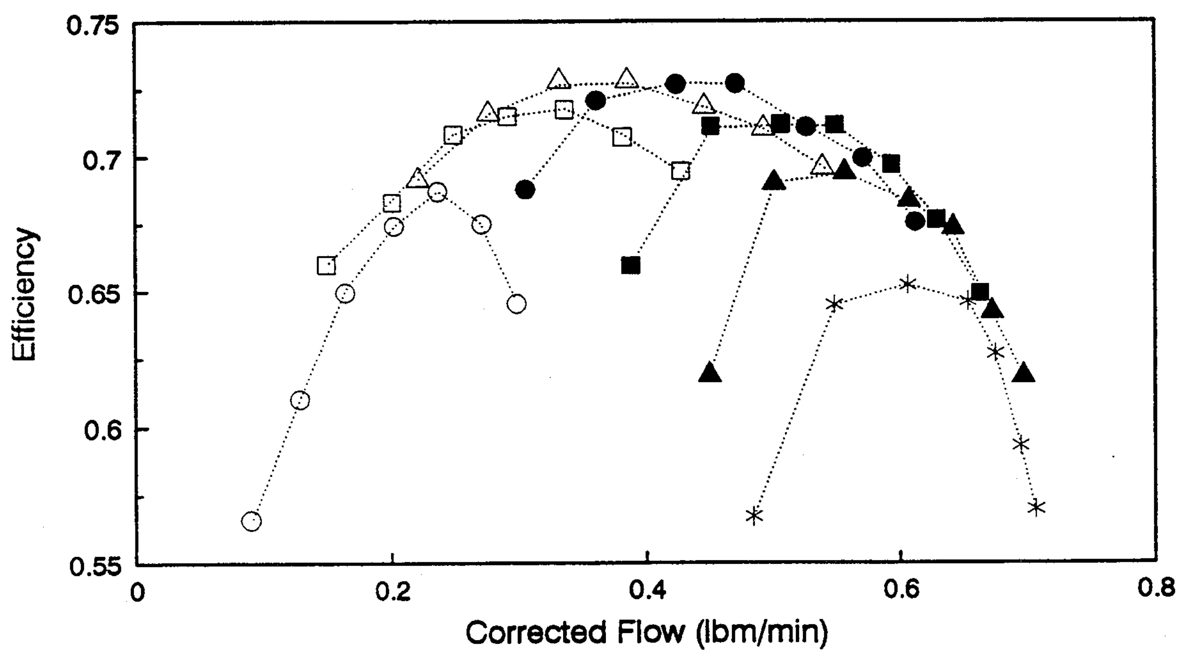


(b) Efficiency Map

Figure VII-3: High Pressure Compressor Map for Example 6

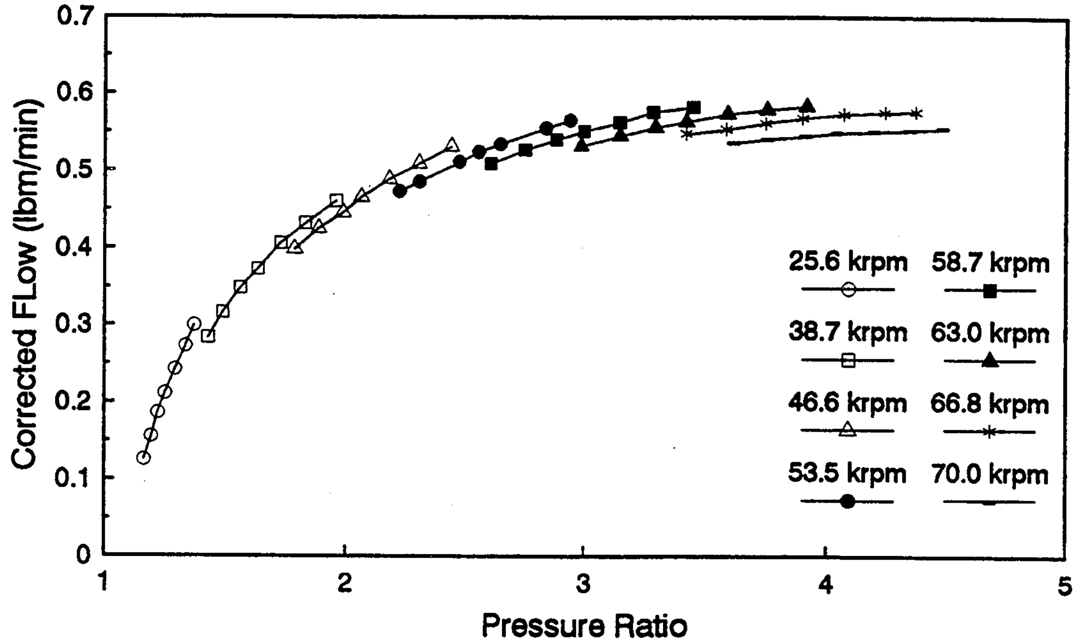


(a) Flow Map

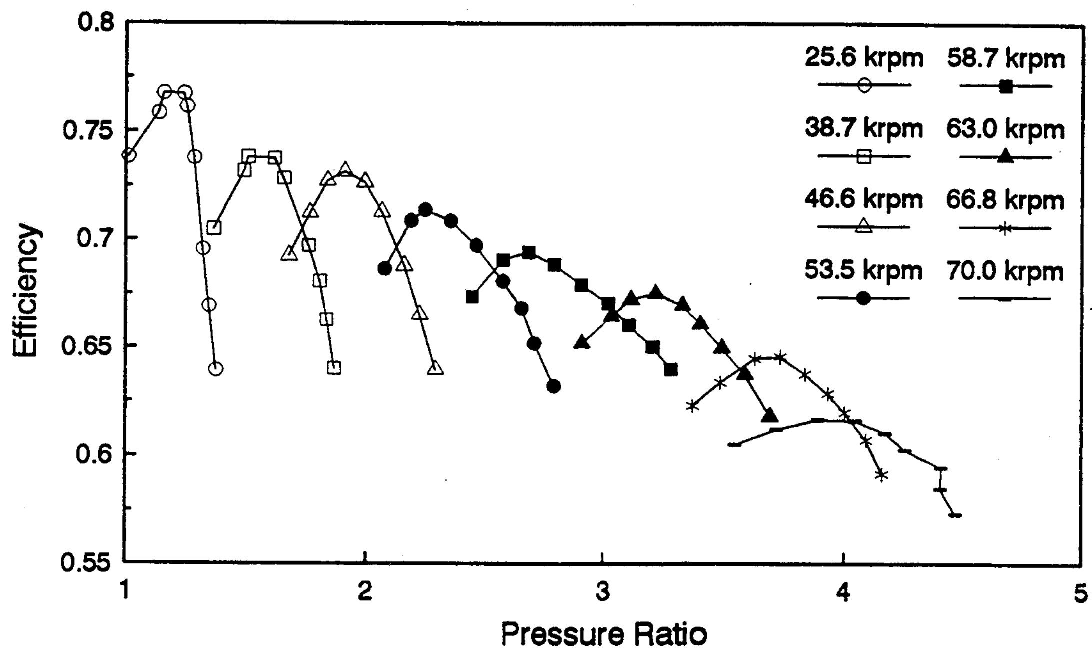


(b) Efficiency Map

Figure VII-4: Low Pressure Compressor Map for Example 6

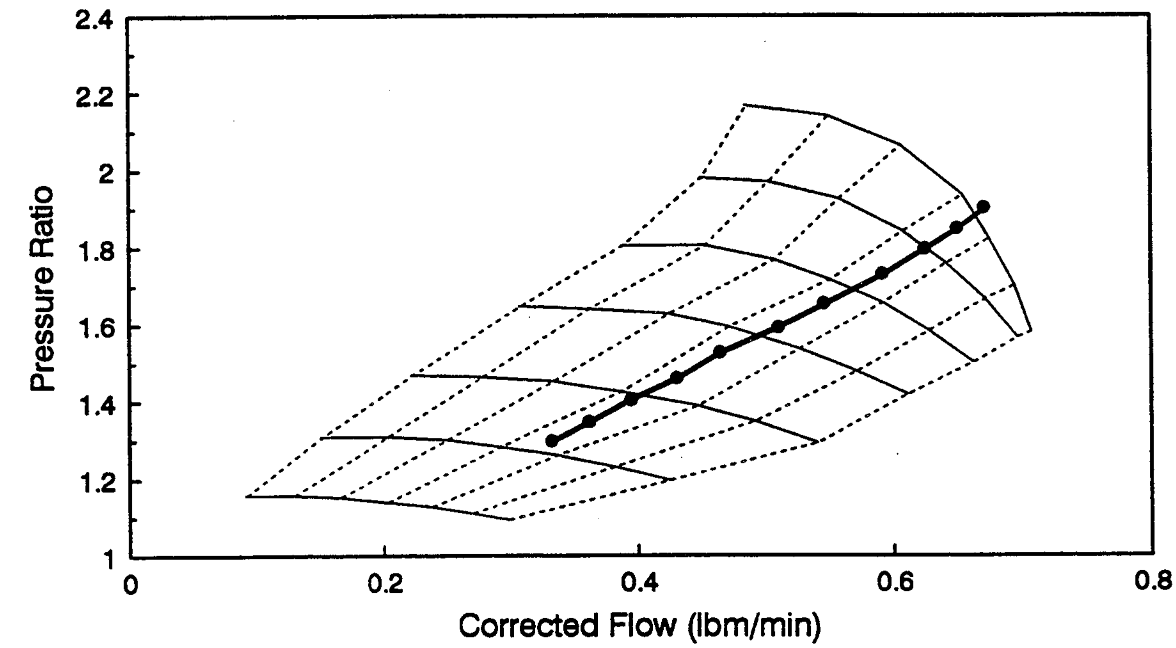


(a) Turbine Flow Map

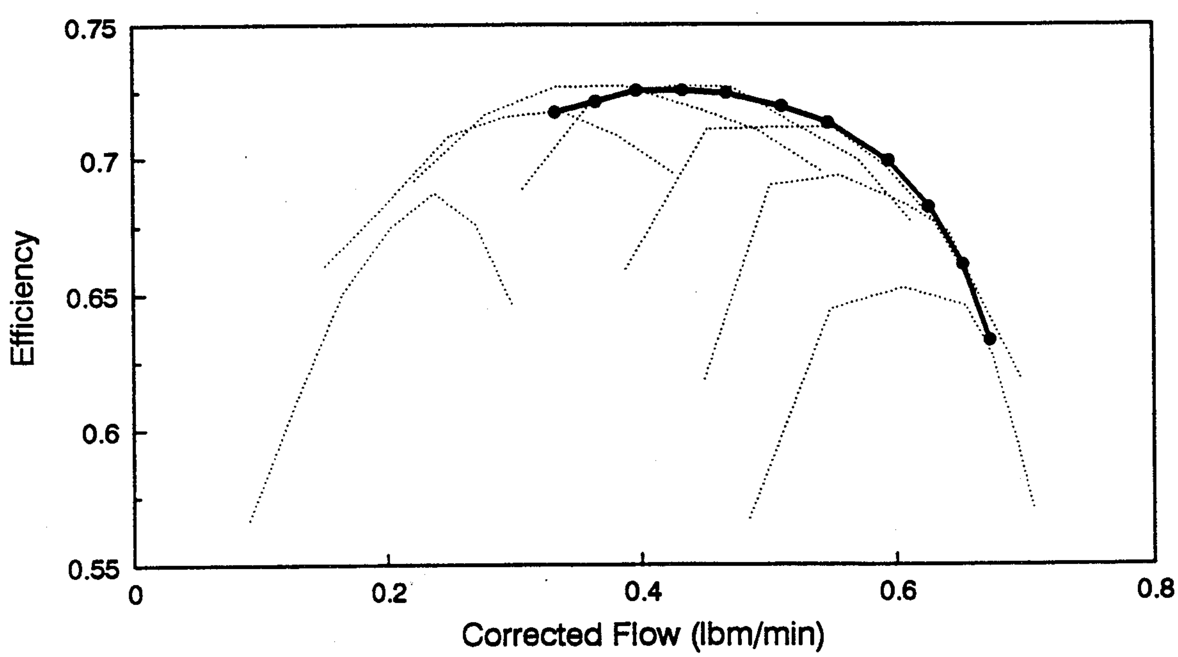


(b) Turbine Efficiency Map

Figure VII-5: Turbine Map for Example 6

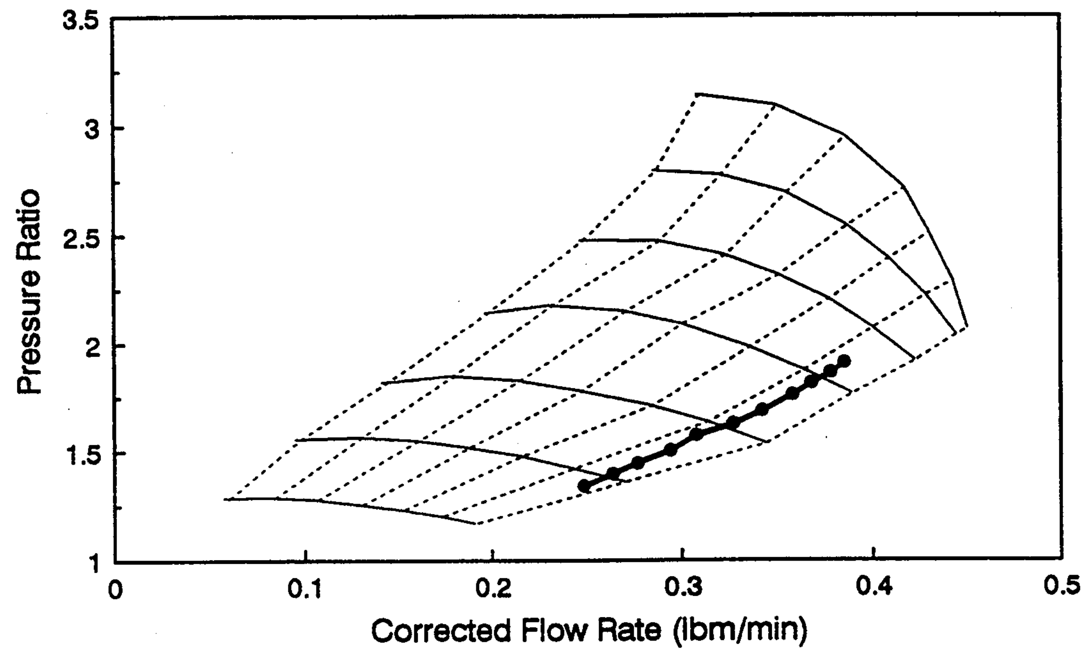


(a) Flow Map

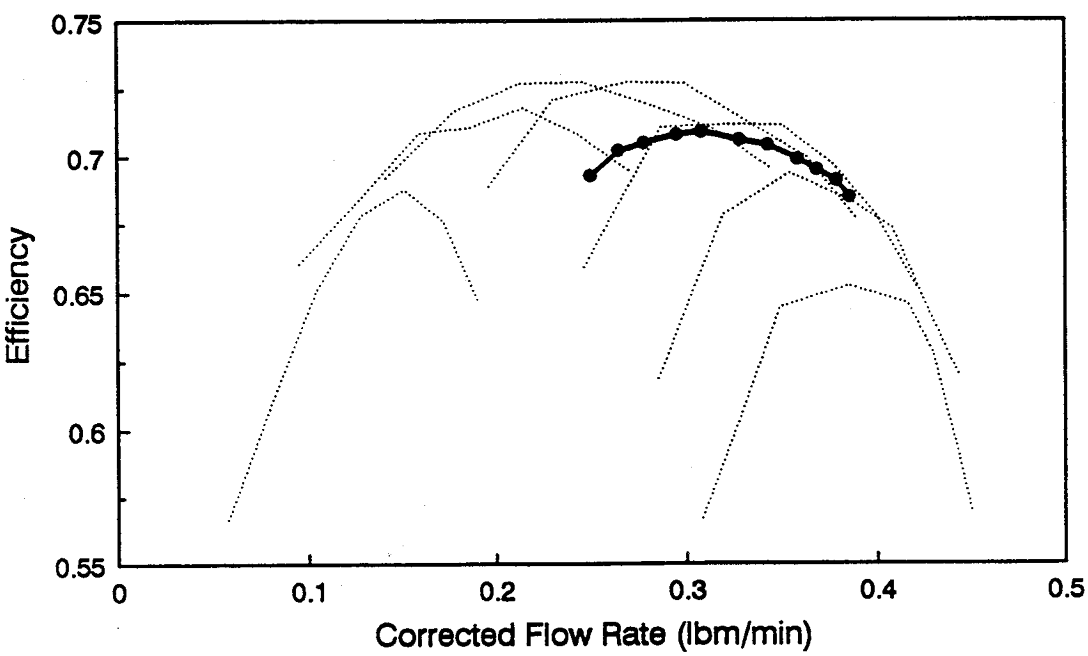


(b) Efficiency Map

Figure VII-6: Low Pressure Compressor Operating Line

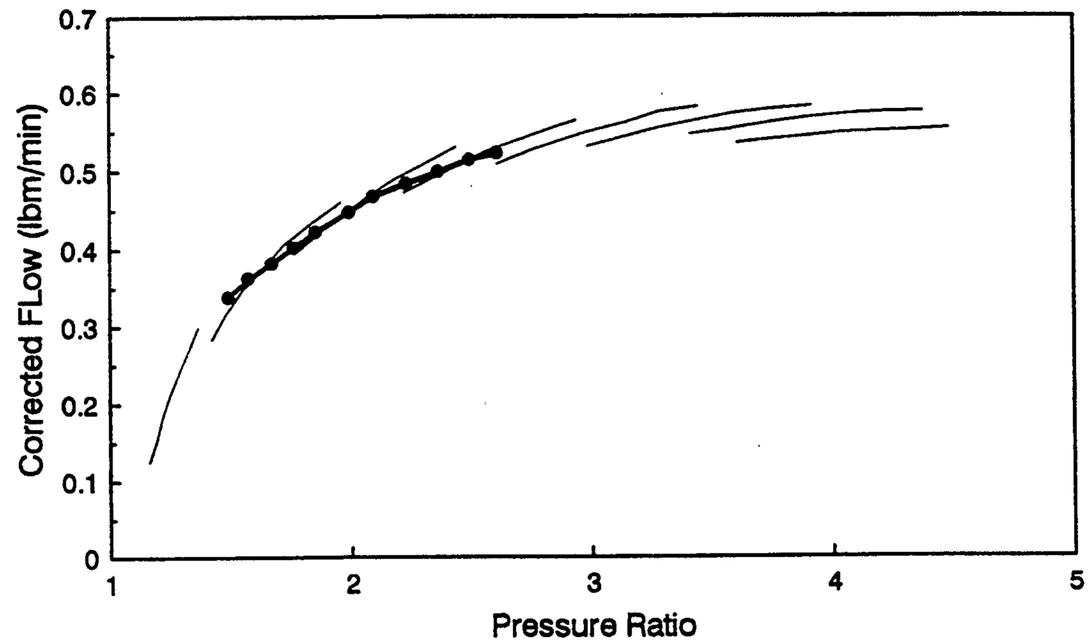


(a) Flow Map

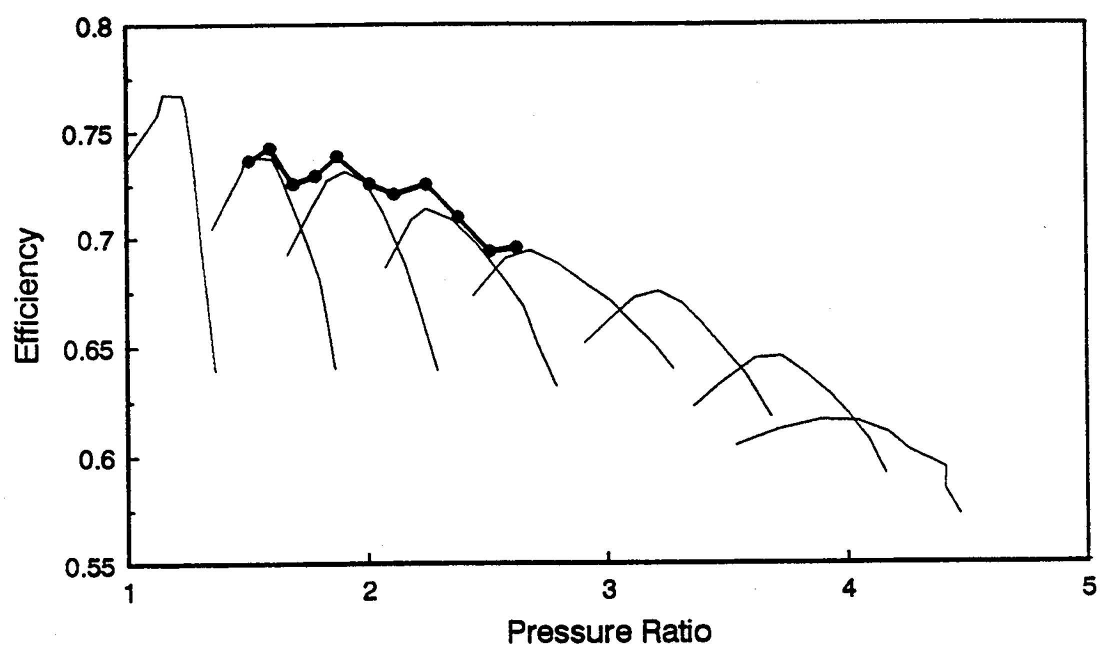


(b) Efficiency Map

Figure VII-7: High Pressure Compressor Operating Line



(a) Turbine Flow Map



(b) Turbine Efficiency Map

Figure VII-8: Turbine Operating Line

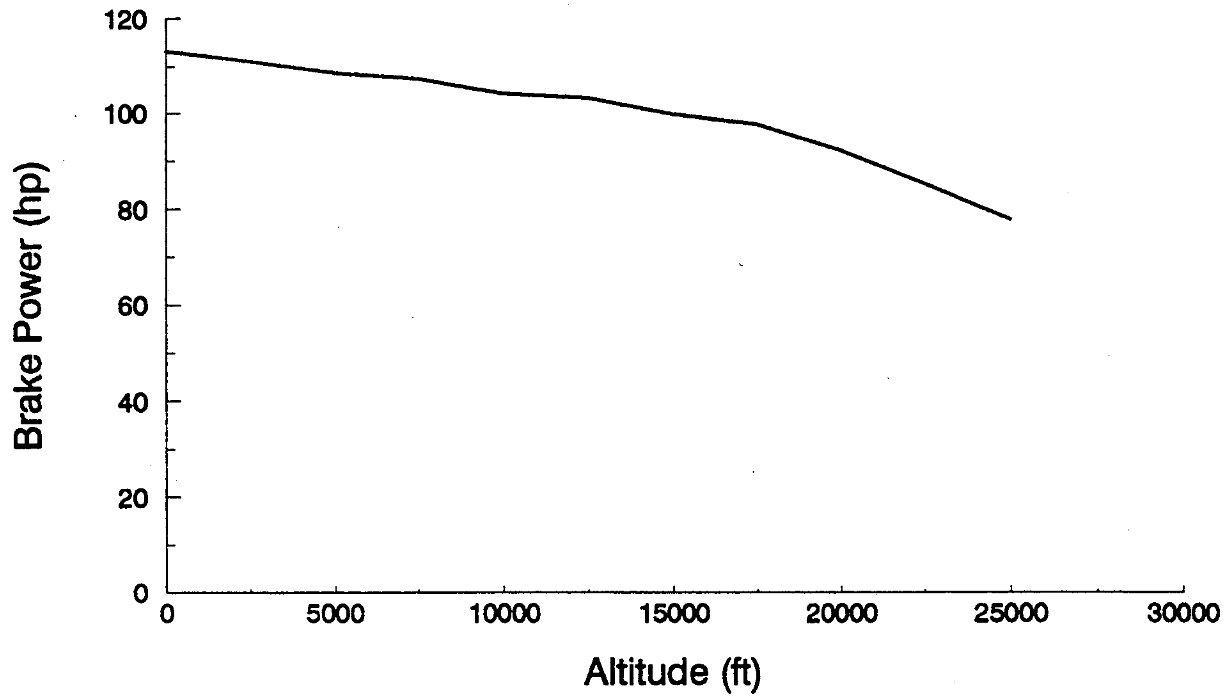


Figure VII-9: Brake Power v. Altitude for Example 6

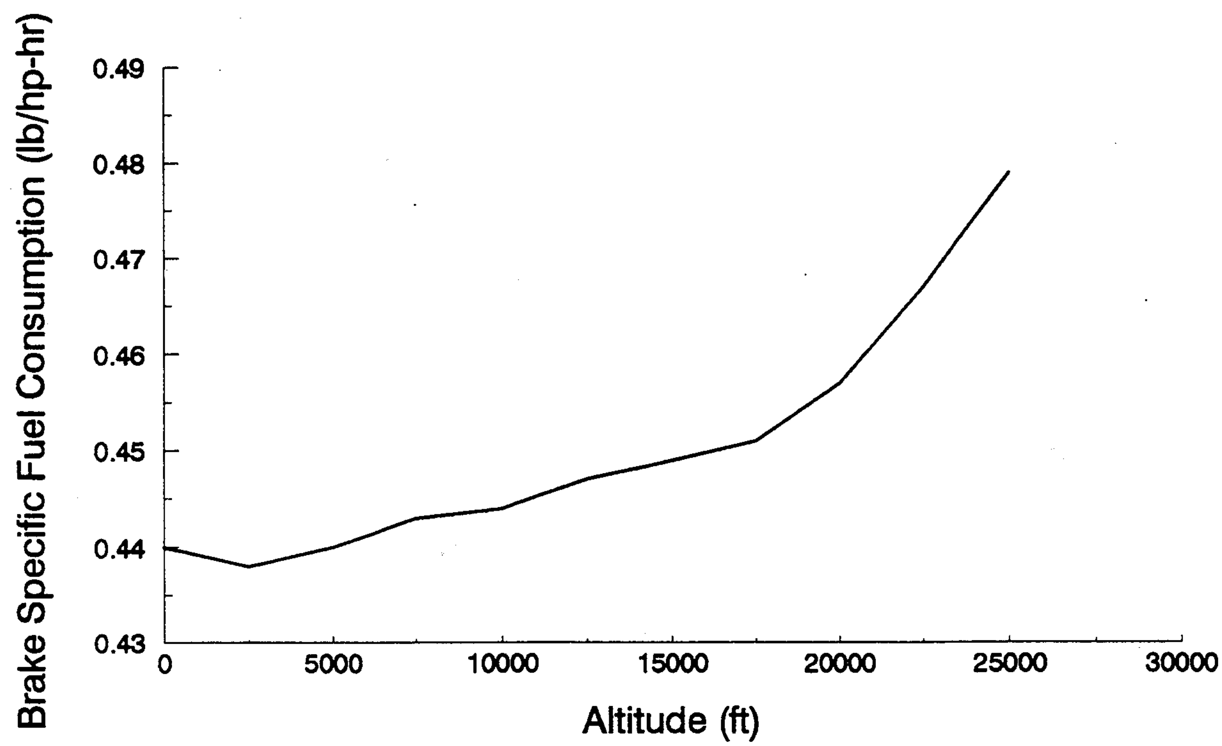


Figure VII-10: Brake Specific Fuel Consumption v. Altitude for Example 6

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APPENDIX A : A PC - COMPATIBLE VERSION OF RCEMAP

A-1: Introduction and Scope

RCEMAP as described in the preceding sections of this report was developed on a VAX mainframe computer and requires this class of machine, or the equivalent, in order to run successfully. While presenting earlier versions, it became clear that a DOS/PC-based variant of RCEMAP would be accessible and potentially useful to a much larger class of users. As a result of major price reductions and performance improvements that have occurred since 1991, the best modern PCs are now approaching workstation computing power but are significantly less expensive. More than 90% of all existing computers are now PCs, and the current trends indicate that such a ratio will be maintained or increased in the foreseeable future.

It was decided to port RCEMAP code to a form that would be compatible not only with a typical PC, but also with one of the most prevalent operating systems: MS-DOS. An available MS Fortran v. 3.3 compiler was used to compile and link executable code after the minimum necessary modifications were made to the original VAX VMS Fortran. Due to the inherent memory limitations of DOS itself, it was found necessary to segment the original code into two parts, each of which is small enough ($<$ 640 Kb) to be run in a "stand-alone" mode under DOS. In what follows, these two parts will be referred to as "RCTC", standing for Rotary Combustion TurboCharged; and "TMFT", standing for Turbo-Match ForTran. RCTC covers all internal processes and parts of the rotary engine itself. TMFT covers all turbomachinery and related external gas flow systems. The thermodynamic interface between RCTC and TMFT was simplified, as discussed below, so that each segment can run alone for one complete cycle. A simple DOS batch program (REBAT.BAT) was used to successively run TMFT and RCTC, prepare and manipulate some auxiliary data files to communicate between them, and check convergence criteria to obtain a matched solution. It may be observed from this description that the batch file REBAT.BAT, together with the auxiliary files, serves the function of an overlay structure (the available MS Fortran 3.3 LINKer does not support this feature).

The approach outlined above resulted in a simplified version of RCEMAP which can run effectively under DOS 5.0 on any modern coprocessed i386DX/ or higher machine. (The examples presented below were run on an i486/33Mhz machine with 4 Mb of memory.) There are, however, some drawbacks of which the user should be aware. First and most important is the 640Kb per program memory limitation that is inherent in DOS itself. This forced the use of the segmented or pseudo-overlay type structure mentioned above. Since both TMFT and RCTC require iterative solutions, the segmented structure forces TMFT to iterate to completion for each step or trial solution in the RCTC iteration. This results in some CPU time penalty, although probably not a major one since TMFT runs much faster than RCTC. More limiting is the fact that the iteration between TMFT and RCTC must now be performed on a static basis. That is, the infinite-plenum model (see Chapter III, section G) must be used to couple the turbomachinery to the rotary engine core. This means the pressures, temperatures and other engine-to-turbocharger thermodynamic matching conditions are considered to be constant over one complete rotary engine cycle of 1080°. The dynamic "emptying-and-filling" manifold model discussed elsewhere in this report is not practical to use in a segmented structure because the matching conditions then vary continuously during the cycle; the iteration described in Section A-4 (below) would need to be repeated 1080 times to complete one cycle! Other limitations are compiler-specific and might be eliminated by the use of a different version. For instance, MS Fortran v.3.3 does not support the NAMELIST input feature; hence for the purposes of this Appendix, equivalent conventional input files and "read" statements were incorporated. And as previously implied, the use of an overlaying LINKer should result in a more streamlined structure than what will be seen in Section A-4.

The three following sections will describe and illustrate TMFT, RCTC and REBAT.BAT. Examples including input and output files are given in each case.

A-2: TMFT (Turbocharger Matching Code Turbo-Match ForTran)

Introduction

TMFT is a stand-alone version of RCEMAP's turbocharger matching routines. Using user-input compressor and turbine maps and operating conditions, TMFT varies turbocharger speed until compressor and turbine work match (the turbocharger is matched). Inputs to TMFT are air and fuel flow rates, ambient pressure and temperature, engine (pre-turbine) exhaust gas temperature and compressor and turbine maps. Outputs are the turbocharger performance parameters, including compressor and turbine pressure ratios and efficiencies, wastegate flow rate and aftercooler discharge temperature. TMFT requires approximately 271 kB of DOS memory and has a short run time (about 7 CPU seconds for an "average" case on a VAX 11/780 or about 12 – 15 seconds on a 486/33 PC). It also doesn't require very many inputs. Table A-2.1 shows the contents of the files TMA and TMB (which contain the source-code lines for TMFT) and the differences between TMFT routines and the equivalent routines in the original program, RCEMAP.

TMATCH has several uses. First, TMATCH evaluates candidate compressors and turbines as turbocharger components. Second, it estimates initial conditions (manifold temperatures and pressures) for RCEMAP. Finally, as described in the introduction of this Appendix, TMFT can be run with the PC-based rotary engine thermodynamic performance code RCTC to simulate a turbocharged rotary engine on the PC.

Running TMFT

To run TMFT, the user must create an executable version of the source code, then create and fill the input files RT.DAT, TMATCH.INP and TURB.DAT. Instructions for using the MS-FORTRAN compiler to produce an executable code are presented below. Users who already have an executable version of TMFT may skip the next three paragraphs and begin reading again in the Inputs section below.

Table A-2.1: TMFT Source Code Description

File	Subroutines and Functions	Changes
TMA	TMATCH(main), COMP1, COMP2, MATCHX, FINDPR, TURPR, AFTERC	TMATCH added to call COMP1 and COMP2. Inputs via formatted READ statements in TMATCH rather than via namelists in in RCEMAP. All outputs to unit 6 redirected to output file TMATCH.OUT
TMB	TREAD, TLOOK, MTHERM, HPROD, CLDPRD, MFLRT, SPLNQ1	No changes from versions in RCEMAP

As previously noted, an available MS-FORTRAN v. 3.3 compiler was used for the purposes of this Appendix. Details on the operation of this software may be found in the corresponding user's guide, "Microsoft FORTRAN Compiler v. 3.3 for the MS DOS Operating System Users Guide" – Microsoft Corp. document number 8206L-330-05. The procedures used here are briefly outlined below. It should be understood that these procedures are both compiler-specific and DOS-specific. However, the resulting executable code should run without modification on any coprocessed DOS machine which has adequate memory and a 386 DX or higher CPU.

The source code for TMFT is found in the files TMA and TMB. To create an executable file using the MS-FORTRAN compiler version 3.3, first compile TMA and TMB. MS-FORTRAN version 3.3 uses a two-step compiler. The appropriate commands are `FOR1` followed by `PAS2`. In each case the user supplies suitable file names in response to compiler prompts. For example, compile TMFT by typing the following statements at the C:\ prompt:

```
FOR1 TMA
FOR1 TMB
PAS2 TMA
PAS2 TMB
```

Performing `FOR1` and `PAS2` results in "LINKable" object (`.OBJ`) versions of each file. The above statements create two object (`.OBJ`) files called TMA.OBJ and TMB.OBJ. The object files are then LINKed to form executable (`.EXE`) code. To create the executable code, the appropriate C:\ prompt command is `LINK` followed by an argument list of `.OBJ` files:

```
LINK filename1+filename2+filename3+...
```

An appropriate executable filename and any desired libraries are then added in response to `LINK`er prompts. To `LINK TMFT`, type the following line at the C:\ prompt:

```
LINK TMA+TMB
```

Alternatively, just type `LINK` and supply the argument list in response to the first `LINK`er prompt. Then add the executable file name (`TMFT`) and the desired library (usually `MATH`) after further prompts. This procedure results in the executable file `TMFT.EXE`. To run `TMFT.EXE`, type `TMFT` at the C:\ prompt.

Inputs

TMFT has three input files: RT.DAT, TMATCH.INP and TURB.DAT. RT.DAT provides TMFT with air and fuel mass flow rate, engine (pre-turbine) discharge temperature and, when TMFT is called iteratively with the rotary engine performance program, the number of times TMFT has been called. Other engine operating conditions and turbocharger configuration information are found in TMATCH.INP. Compressor and turbine maps are provided in TURB.DAT. Input file TURB.DAT is the same as the file TURB.DAT used in RCEMAP (see Chapter V of this user's guide for a full description of TURB.DAT). The three input files are described in detail below.

RT.DAT is the smallest input file. It consists of one line of data containing seven entries. The user should keep a back-up copy of the original RT.DAT, since this is repeatedly modified during the iterative matching process described in section A-4. Also, RT.DAT may be erased if TMFT encounters an error or cannot match a turbocharger configuration. A sample of the file RT.DAT is shown in Table A-2.2. The entries (from left to right) are the air flow rate (in $\frac{lb_m}{hr}$), fuel flow rate ($\frac{lb_m}{hr}$), pre-turbine engine exhaust gas temperature (K), engine intake manifold pressure (atm), engine intake manifold temperature (K), engine exhaust manifold pressure (turbine inlet pressure, atm) and the number of times TMFT has been called (only used in concert with RCTC). The first three values and the seventh value are inputs to TMFT; the fourth, fifth and sixth entries are outputs and can either be estimates or left blank. The FORTRAN format statement for reading and writing RT.DAT is `(2X,F8.3,2X,F8.3,2X,F8.3,32X,I2)`.

Table A-2.2: Sample File RT.DAT

```
2168.023    66.796   976.722     2.710   359.997     2.053   9
```

<u>TMATCH.INP</u> contains other turbocharger operating conditions and information on the whereabouts of the compressor and turbine maps. Table A-2.3 is a sample file for TMATCH.INP. Running TMFT with the input files in Tables A-2.2 and A-2.3 yields the operating point (speed, pressure ratios, efficiencies) of a wastegated aftercooled turbocharger with one compressor and one turbine for an engine whose air flow rate is 2168.023 $\frac{lbm}{hr}$ and whose fuel flow rate is 66.796 $\frac{lbm}{hr}$. Table A-2.4 provides general descriptions for the variables in TMATCH.INP and their units.

Compressor and turbine maps are fed to TMFT via the input file TURB.DAT. Although only 3 compressor maps (6 for a two-compressor turbocharger) and 2 turbine maps are used for a given run, TURB.DAT may contain more maps than are used. The number of maps is limited only by by the storage space allocated to the maps, up to the preset limit in the routine which reads the maps (20,000 data points). Each map begins with a map reference number and title line. The next card is not used in this program but must have the proper form (see Table VII-8, in the main body of this guide). The remaining cards give turbine and compressor performance data. There should be three files associated with each compressor: a flow rate file, an efficiency file and a pressure ratio file. There should be two for each turbine: a flow rate file and an efficiency file. The last card in each table should read `EOT` (End of Table). A sample for TURB.DAT is listed in Table VII-8, in the main body of the user's guide. Further descriptions of the input file TURB.DAT are provided in Chapter V of this manual.

Table A-2.3: Example File for TMATCH.INP

```
1
1
2
3
11
12
13
7
8
        273.
          1.
0
        545.
       13.94
        519.
      14.688
        519.
      14.688
         1.5
         2.1
        0.04
         0.7
       0.030
      400.00
      325.00
       0.400
```

Table A-2.4: Variables in File TMATCH.INP

Variable	Description	Units
NCOMP	Number of compressor (1 or 2)	
IC1	Compressor flow rate map number**	
IC2	Compressor efficiency map number**	
IC3	Compressor pressure ratio map number**	
IC4*	High pressure compressor flow rate map number**	
IC5*	High pressure compressor efficiency map number**	
IC6*	High pressure compressor pressure ratio map number**	
IT1	Turbine flow rate map number**	
IT2	Turbine efficiency map**	
TEXH	Engine exhaust gas temperature (pre-turbine)	K
TATM	Atmospheric temperature	K
PATM	Atmospheric pressure	atm
II	If II = 1, maps are printed to output file; otherwise, II=0	
CREFT1	Compressor reference temperature†	°R
CREFP1	Compressor reference pressure†	psi
TREFT	Turbine reference temperature†	°R
TREFP	Turbine reference pressure†	psi
CREFT2*	Low pressure compressor reference temperature†	°R
CREFP2*	Low pressure compressor reference pressure†	psi
PWG1	Comp. discharge press. at which wastegate begins to open	atm
PWG2	Comp. discharge press. at which wastegate is fully open	atm
AWG	Wastegate area	cm^2
CDWG	Wastegate discharge coefficient	

* Only used when NCOMP = 2

** Map numbers refer to the map's position within the file TURB.DAT and don't refer to the map reference number in the map title line. The first map (at the top of the file) is number 1 and the rest are numbered sequentially.

† Used to convert actual speed and flow rates to referred values.

Outputs

A sample output file from TMFT is listed in Table A-2.5. The top half of the file is an echo of the input data. Following these echoed data, there is information on the performance of the program: the number of turbocharger speed iterations and the eventual uncertainty in the speed (in rpm$\times$ 1000). Next, compressor, turbine and, for a two-compressor turbocharged engine, low pressure compressor performance data are printed. Finally, station temperature and pressure are printed. For the single compressor turbocharged engine, the station numbers have the following meanings: station 1 $\rightarrow$ atmospheric conditions; station 2 $\rightarrow$ compressor exit conditions; station 2S $\rightarrow$ compressor exit conditions if the compressor provided isentropic compression; station 3 $\rightarrow$ aftercooler discharge conditions; stations 4 – 6 $\rightarrow$ not used; station 7 $\rightarrow$ turbine inlet conditions; 8 $\rightarrow$ turbine discharge conditions; and station 8S $\rightarrow$ turbine discharge conditions if the turbine provided isentropic expansion.

Table A-2.5: Sample Output File from TMFT

```
********** TMATCH.OUT **********
********** TMFT OUTPUT *********


ECHO OF INPUTS:

  AIR AND FUEL FLOW RATES
    AIR MASS FLOW RATE (LBM/HR)   =    2168.02
    FUEL MASS FLOW RATE (LBM/HR)  =     66.796
  COMPRESSOR AND TURBINE MAP NUMBERS
    NUMBER OF COMPRESSORS         =          1
    COMPRESSOR FLOW MAP NO        =          1
    COMPRESSOR EFFICIENCY MAP NO  =          2
    COMPRESSOR PRESS RATIO MAP NO =          3
    TURBINE FLOW MAP NUMBER       =          7
    TURBINE EFFICIENCY MAP NUMBER =          8
    LOW PRESS COMPR FLOW MAP NO   =         11
    LOW PRESS COMP EFFIC. MAP NO  =         12
    LOW PRESS COMP PR MAP NO      =         13
  EXHAUST TEMPERATURE AND ATMOSPHERIC CONDITIONS
    PRE-TURBINE EXHAUST TEMP (K)  =     976.72
    AMBIENT TEMPERATURE (K)       =    273.000
    AMBIENT PRESSURE (ATM)        =      1.000
  MAP REFERNCE TEMPERATURES AND PRESSURES
    COMPRESSOR REF TEMP (DEG R)   =     545.00
    COMPRESSOR REF PRESSURE (PSI) =     13.940
```

```
  TURBINE REF TEMP (DEG R)       =     519.00
  TURBINE REF PRESSURE (PSI)     =     14.688
WASTEGATE (WG) PARAMETERS
  WG CRACKING PRESSURE (ATM)     =      1.500
  WG FULLY OPEN PRESSURE (ATM)   =      2.100
  WG AREA (SQ CM)                =     0.0400
  WG DISCHARGE COEFFICIENT       =      0.700
AFTERCOOLER (AFC) DATA
  AFC GAS PRESSURE DROP (ATM)    =      0.030
  GAS HEAT TRANS COEFF (W/M2-K)  =     400.00
  AFC COOLANT INLET TEMP (K)     =     325.00
  COOLANT TUBE AREA (CM2)        =      0.400
```

```
>>> ITERATION NUMBER  30
    SPEED CONVERGED TO WITHIN =      0.924 krpm
    ALTITUDE    =          0. ft


>>> COMPRESSOR OPERATING CONDITIONS
    PRESSURE RATIO  =     2.740
    MAP INTERPOLATION R  =    1.2969
    CORRECTED FLOW (lbm/min)    =    0.542
    CORRECTED SPEED (rpm/1000) =  108.936
    EFFICIENCY (%)              =   77.202
    ACTUAL MASS FLOW (lbm/hr)   =  2168.02
    ACTUAL SPEED (rpm)          = 103440.3
    POWER (hp)                  = -39.7574


>>> TURBINE OPERATING CONDITIONS
    PRESSURE RATIO  =     2.048
    CORRECTED FLOW (lbm/min)     =    0.467
    CORRECTED SPEED (rpm/1000)   =   56.202
    EFFICIENCY (%)               =   72.070
    WASTEGATE FRACTION OPEN      =   1.0000
    WASTEGATE FLOW RATE (lb/hr)  =     5.95
    % OF FLOW TO WASTEGATE       =   15.968
    ACTUAL MASS FLOW (lbm/hr)    =  1877.97
    ACTUAL SPEED (rpm)           = 103440.3
    POWER (hp)                   =  39.7359
```

>>> STATION TEMPERATURES AND PRESSURES

WORK ERROR = -0.054 %

STATION	TEMPERATURE (K)	PRESSURE (ATM)
1	273.0	1.000
2	390.2	2.740
2S	363.5	2.740
3	360.0	2.710
6	0.0	0.000
7	976.7	2.053
8	881.8	1.000
8S	845.0	1.000

A-3: RCTC (Rotary Combustion Turbocharged Program for the PC)

Introduction

As described in the introduction of this Appendix, major changes to RCEMAP were necessary to enable it to run on a conventional personal computer with a widely available version of FORTRAN. The two most important changes are: the decoupling of the turbocharger and core engine parts of the program and the use of formatted (rather than namelist) inputs. This section of the Appendix is intended to instruct the user on how to run the resulting personal computer version of the core engine program. This version is called RCTC.

Table A-3.1 (on the following page) enumerates the major differences between RCTC and the equivalent routines in RCEMAP.

In brief, RCTC predicts core rotary engine performance, including output, efficiency and fuel consumption. Its inputs include not only the usual inputs for RCEMAP (e.g., engine speed, equivalence ratio, geometry, etc.) but also intake manifold pressure and temperature and exhaust manifold pressure. Recall that RCEMAP sets the manifold pressures and temperatures by itself. Because the manifold conditions are specified in RCTC, they do not vary during the cycle; the manifolds are infinite plena, rather than emptying/filling volumes.

Following is a description of how to compile, link and run RCTC. Because of compiler size limitations, RCTC is stored in five files called R1.FOR, R12.FOR, R2.FOR, R3.FOR and R4.FOR. Instructions on compiling, linking and running a program in MS-FORTRAN v. 3.3 are found in this Appendix in the section describing how to compile and run the program TMFT. Specific commands for compiling, linking and running RCTC are presented below. If the user already has an executable version of RCTC or if he or she is using a different version of FORTRAN, the user can skip the next several paragraphs and begin reading again in the section below called Inputs.

To create an executable version of RCTC, compile the five files and link them. This is accomplished by typing the following commands at the C:\ prompt:

```
FOR1 R1
FOR1 R12
FOR1 R2
FOR1 R3
FOR1 R4
PAS2 R1
PAS2 R12
PAS2 R2
PAS2 R3
PAS2 R4
LINK R1+R12+R2+R3+R4
```

Table A-3.1: RCTC Source Code Description

File	Subroutines and Functions	Changes
R1	RCEMAP	All inputs now from RT.DAT and RCE1.INP.
R12	ROTARY	Namelist inputs changed to formatted inputs. Calls to turbocharger routines COMP1 and COMP2 removed. Turbocharger maps no longer read
R2	CSAVDV, CHMBER, TROCHD, ROTOR, INAREA, XYROTR, ROTROT, HELPHT, IPACD, EPACD, ITRATE, ODERT, DERT1, STEP1, ROOT, INTRP, ERRCHK, TABLE, BUILD, FRCTN, APEXFR	No changes
R3	SIDEFR, FINDP, OILSFR, BEARFR, DCIRC, ROMBRG, PERFOR, LARRY, INTAKE, CMPRES, CMBSTN, EXAUST	Calls to INCALC and EXHMAN removed from INTAKE, CMPRES, CMBSTN, EXAUST
R4	MULTIR, CREVIC, HTDTRO, HTDSID, HTDROT, BTRANS, THOUSC, TSIDEC, TROTOC, QENDH, QENDS, QENDR, FUELDT, MTHERM, HPROD, CLDPRD, FINDT, MFLRT, HEATTX	Namelist inputs converted to formatted reads in HTDROT, HTDTRO and HTDSID.

After issuing the `LINK` command, the user will be prompted for the executable file name and the desired libraries. The executable file name is RCTC. The library `MATH` is used.

Next, create the desired output files in the directory where RCTC will be run. For information on which files should be created, read about the variable `LDEBUG` in Chapter V and Tables V-20, V-21 and Table VI-1. Finally, run RCTC by typing RCTC and return.

The balance of this section describes RCTC inputs and outputs in detail.

Inputs

All inputs to RCTC are also inputs to RCEMAP, so much of the material in this section will refer to the inputs section of the RCEMAP user's guide (Chapter V). To run RCTC, the user must create two input files: RT.DAT and RCE1.INP. Keep in mind that `RT.DAT` get modified at each iteration step. Three of the six values get replaced whenever either RCTC or TMFT runs. Therefore, it is a good idea to save the original values somewhere else.

RT.DAT in RCTC is the same as RT.DAT used in the PC-based turbocharger matching routine TMFT. File RT.DAT contains one line of data, consisting of the air and fuel mass flow rates, the exhaust gas temperature, the intake plenum pressure and temperature, the exhaust plenum pressure and the number of times RCTC has been called (for use when RCTC is called iteratively with TMFT). The format for these numbers is listed in Table A-3.1. The first three entries (air and fuel mass flow rates and exhaust gas temperature) are not used as inputs, so they can be assigned arbitrary values. The user can set the manifold pressure and temperature using TMFT or other suitable means.

RCE1.INP contains all other inputs to RCTC, including geometry, operating conditions, mathematical constants and cooling data. Because namelists are not permissible in the PC-FORTRAN compiler used here, the data are arranged as formatted inputs. The following three tables describe the contents of RCE1.INP. Table A-3.2 shows a sample of RCE1.INP. Table A-3.3 shows the variables corresponding to each entry in the input file and the corresponding FORTRAN format statements. Finally, Tables A-3.4 and A-3.5 provide brief descriptions of each variable in RCE1.INP. The variables in Table A-3.3 are used slightly differently than as described in the inputs section of this user's guide and these differences are explained. For all other variables, the user is referred to tables in the main body of the user's guide for descriptions of the varaibles and ranges of appropriate values for the variables.

Table A-3.2: Sample File RCE1.INP

```
1
1
1         0.0         0.0
1      7500.0      7500.0
1         0.6         0.6
   1     13      5  1991     11
       1.5421     10.6408      7.7114        52.7
        0.017       0.567      0.0822      0.0635
T
        35.99         0.0       300.0
       0.3680      0.1319      0.0059
        -30.0        15.0       0.025         0.0        0.95
         13.8       10.87        0.65        0.70
       -626.3      -229.5       208.7       610.5
         37.0        42.0
3  3  3
       436.48      436.48      436.48
        0.037         0.8         1.0       0.324         0.0
F  F  T  F  F  F  F  F  F  F  F  F  F  F  F
F  F
         10.0         5.0
        0.001       0.001       0.005       0.001
        0.001       0.001       0.001
         0.18        0.07        0.13        0.77
         35.0      0.0813       33.36
         0.18        0.24        0.07        75.0
         0.15        0.06        22.0         6.0         2.0
2        7.81        4.50        10.4     0.01016
2         4.6        6.36        10.4     0.01016
         0.25        7.62       300.0        24.0
          0.8         1.0
3
        350.0       350.0       350.0       350.0       350.0
        350.0       350.0       350.0       350.0       350.0
        350.0       350.0       350.0       350.0       350.0
        350.0       350.0       350.0       350.0       350.0
        350.0       350.0       350.0       350.0       350.0
        350.0       350.0       350.0       350.0       350.0
        0.127       0.635      10.488
        240.0       240.0       240.0
30      400.0       0.416      12.546         1.5
2
         0.63        10.0        0.62
```

	54.7	54.7	54.7		
	2000.0	325.0			
3					
	350.0	350.0	350.0	350.0	350.0
	350.0	350.0	350.0	350.0	350.0
	350.0	350.0	350.0	350.0	350.0
	350.0	350.0	350.0	350.0	350.0
	350.0	350.0	350.0	350.0	350.0
	350.0	350.0	350.0	350.0	350.0
	600.0	600.0	600.0	600.0	600.0
	600.0	600.0	600.0	600.0	600.0
	600.0	600.0	600.0	600.0	600.0
	600.0	600.0	600.0	600.0	600.0
	600.0	600.0	600.0	600.0	600.0
	600.0	600.0	600.0	600.0	600.0
	0.127	0.635	10.488		
	240.0	240.0	240.0		

Table A-3.3: Variables and Formats in RCE1.INP

NROTOR					(2X,I1)
IFUELT					(2X,I1)
NALT	ALTL	ALTH			(2X,I2,2(2X,F11.4))
NPRM	RPML	RPMH			(2X,I2,2(2X,F11.4))
NPHI	PHIL	PHIH			(2X,I2,2(2X,F11.4))
ICASE	IDAY	IMONTH	IYEAR	MAXITS	(5(2X,I4))
ECCEN	ROTRAD	DEPTH	VFLANK		(3X,4(2X,F11.4))
AREALK	CREVOL	SZOVER	CLRNCE		(3X,4(2X,F11.4))
LFIRE					(2X,L1)
FRATE	EGR	TEGR			(3X,3(2X,F11.4))
ANCIL1	ANCIL2	ANCIL3			(3X,3(2X,F11.4))
TSPARK	TMAX	DQDTMX	XBZERO	XBSTOP	(3X,5(2X,F11.4))
IPA	EPA	CDIP	CDEP		(3X,4(2X,F11.4))
TIPO	TIPC	TEPO	TEPC		(3X,4(2X,F11.4))
THIPO	THEPO				(3X,2(2X,F11.4))
IHTPRO	IRTPRO	ISTPRO			(3(2X,I1))
TROTI	TSIDI	THOUSI			(3X,3(2X,F11.4))
CONHT	EXPHT	CON1	CON2	CON3	(3X,5(2X,F11.4))
LDEBUG(1)	LDEBUG(2) ---> LDEBUG(15)				(15(2X,L1))
LBRIEF	LSI				(2(2X,L1))
TPRINT	TPRINX				(3X,2(2X,F11.4))
PCONV	TCONV	XMCONV	THCONV		(3X,4(2X,F11.4))
TRCONV	PMCONV	EMCONV			(3X,3(2X,F11.4))
ABASE	AFRC1	AFRC2	AHEIG		(3X,4(2X,F11.4))
AMASS	ARAD	FSPRI			(3X,3(2X,F11.4))
SIDEB	SIDEH	SIDECF	SIDEF		(3X,4(2X,F11.4))
SOILB	SOILCF	SOILF	SOILR	SOILP	(3X,5(2X,F11.4))
NRB	DRB	WRB	VRB	CRB	(2X,I1,4(2X,F11.4))
NMB	DMB	WMB	VMB	CMB	(2X,I1,4(2X,F11.4))
EPTHIK	EXHPL	TPOUT	TCONP		(3X,4(2X,F11.4))
EXHPEM	FEXHP				(3X,2(2X,F11.4))
NHML					(2X,I1)
HTCOOL(1 ---> 30)					(5X,F11.4,2X,F11.4,2X,F11.4,2X,F11.4,2X,F11.4)
HTHIK (1 ---> 3)					(3X,3(2X,F11.4))
HCOND (1 ---> 3)					(3X,3(2X,F11.4))
NUBES	TDAT	TCONL	BDOIL	DTUBES	(1X,I2,4(2X,F11.4))
NRML					(2X,I1)
RTHIK (1 ---> 3)					(3X,3(2X,F11.4))
RCOND (1 ---> 3)					(3X,3(2X,F11.4))
RHCOOL	RTCOOL				(3X,2(2X,F11.4))
NSML					(2X,I1)
STCOOL(1 ---> 30)					(5X,F11.4,2X,F11.4,2X,F11.4,2X,F11.4,2X,F11.4)
SHCOOL(1 ---> 30)					(5X,F11.4,2X,F11.4,2X,F11.4,2X,F11.4,2X,F11.4)

STHIK (1 ---> 3)	(3X,3(2X,F11.4))
SCOND (1 ---> 3)	(3X,3(2X,F11.4))

Table A-3.4: Descriptions of RCE1.INP Variables

Variable	Location	Comments
NALT	Tables V-1 and V-2	When TMFT and RCTC are run together (using REBAT) NALT must equal 1
ALTL	Tables V-1 and V-2	When TMFT and RCTC are run together, set ALTL = ALTH.
ALTH	Tables V-1 and V-2	When TMFT and RCTC are run together, set ALTL = ALTH
NRPM	Tables V-1 and V-2	When TMFT and RCTC are run together, set NRPM equal to 1.
RPML	Tables V-1 and V-2	When TMFT and RCTC are run together, set RPML = RPMH.
RPMH	Tables V-1 and V-2	When TMFT and RCTC are run together, set RPML = RPMH.
NPHI	Tables V-1 and V-2	When TMFT and RCTC are run together, set NPHI equal to 1.
PHIL	Tables V-1 and V-2	When TMFT and RCTC are run together, set PHIL = PHIH.
PHIH	Tables V-1 and V-2	When TMFT and RCTC are run together, set PHIL = PHIH.

Table A-3.5: Table Locations of RCE1.INP Variables

Variable	Location	Variable	Location
NROTOR	Tables V-1 and V-2	IFUELT	Tables V-1 and V-2
ICASE	Tables V-4 and V-5	IDAY	Tables V-4 and V-5
IMONTH	Tables V-4 and V-5	IYEAR	Tables V-4 and V-5
MAXITS	Tables V-4 and V-5	ECCEN	Tables V-8 and V-9
ROTRAD	Tables V-8 and V-9	DEPTH	Tables V-8 and V-9
VFLANK	Tables V-8 and V-9	AREALK	Tables V-8 and V-9
CREVOL	Tables V-8 and V-9	SZOVER	Tables V-8 and V-9
CLRNCE	Tables V-8 and V-9	LFIRE	Tables V-6 and V-7
FRATE	Not used currently	EGR	Tables V-6 and V-7
TEGR	Tables V-6 and V-7	ANCIL1	Tables V-6 and V-7
ANCIL2	Tables V-6 and V-7	ANCIL3	Tables V-6 and V-7
TSPARK	Tables V-10 and V-11	TMAX	Tables V-10 and V-11
DQDTMX	Tables V-10 and V-11	XBZERO	Tables V-10 and V-11
XBSTOP	Tables V-10 and V-11	IPA	Tables V-12 and V-13
EPA	Tables V-12 and V-13	CDIP	Tables V-12 and V-13
CDEP	Tables V-12 and V-13	TIPO	Tables V-12 and V-13
TIPC	Tables V-12 and V-13	TEPO	Tables V-12 and V-13
TEPC	Tables V-12 and V-13	THIPO	Tables V-12 and V-13
THEPO	Tables V-12 and V-13	IHTPRO	Tables V-14 and V-15
IRTPRO	Tables V-14 and V-15	ISTPRO	Tables V-14 and V-15
TROTI	Tables V-14 and V-15	TSIDI	Tables V-14 and V-15
THOUSI	Tables V-14 and V-15	CONHT	Tables V-14 and V-15
EXPHT	Tables V-14 and V-15	CON1	Tables V-14 and V-15
CON2	Tables V-14 and V-15	CON3	Not used (set equal to 0).
LDEBUG	Tables V-20 and V-21	LSI	Not used
TPRINT	Tables V-20 and V-21	TPRINX	Tables V-20 and V-21
PCONV	Tables V-22 and V-23	TCONV	Tables V-22 and V-23
XMCONV	Tables V-22 and V-23	THCONV	Tables V-22 and V-23
TRCONV	Tables V-22 and V-23	PMCONV	Tables V-22 and V-23
EMCONV	Tables V-22 and V-23	ABASE	Tables V-28 and V-29
AFRC1	Tables V-28 and V-29	AFRC2	Tables V-28 and V-29
AHEIG	Tables V-28 and V-29	AMASS	Tables V-28 and V-29
ARAD	Tables V-28 and V-29	FSPRI	Tables V-28 and V-29
SIDEB	Tables V-30 and V-31	SIDEH	Tables V-30 and V-31
SIDECF	Tables V-30 and V-31	SIDEF	Tables V-30 and V-31
SOILB	Tables V-32 and V-33	SOILCF	Tables V-32 and V-33
SOILF	Tables V-32 and V-33	SOILR	Tables V-32 and V-33
SOILP	Tables V-32 and V-33	NRB	Tables V-36 and V-37
DRB	Tables V-36 and V-37	WRB	Tables V-36 and V-37
VRB	Tables V-36 and V-37	CRB	Tables V-36 and V-37
NMB	Tables V-38 and V-39	DMB	Tables V-38 and V-39
WMB	Tables V-38 and V-39	VMB	Tables V-38 and V-39

CMB	Tables V-38 and V-39	EPTHIK	Tables V-34 and V-35
EXHPL	Tables V-34 and V-35	TPOUT	Tables V-34 and V-35
TCONP	Tables V-34 and V-35	EXHPEM	Tables V-34 and V-35
FEXHP	Tables V-34 and V-35	NHML	Tables V-43 and V-44
HTCOOL	Tables V-43 and V-44	HTHIK	Tables V-45 and V-46
HCOND	Tables V-45 and V-46	NTUBES	Tables V-47 and V-48
TSAT	Tables V-47 and V-48	TCONL	Tables V-47 and V-48
CBOIL	Tables V-47 and V-48	DTUBES	Tables V-47 and V-48
NRML	Tables V-53 and V-54	RTHIK	Tables V-55 and V-56
RCOND	Tables V-55 and V-56	RHCOOL	Tables V-53 and V-54
RTCOOL	Tables V-53 and V-54	NSML	Tables V-49 and V-50
STCOOL	Tables V-49 and V-50	SHCOOL	Tables V-49 and V-50
STHIK	Tables V-51 and V-52	SCOND	Tables V-51 and V-52

A-4: REBAT.BAT

As explained above, RCTC is a stand-alone subset of RCEMAP's rotary engine simulation routines. It is considered to be fed with inlet air from an "infinite plenum" at known constant conditions and to exhaust to a known constant pressure in another infinite plenum. RCTC then determines the airflow, shaft power output, exhaust gas temperature and other operating conditions consistent with the plenum data and other inputs. Similarly, TMFT is a stand-alone version of the turbomachinery-related routines included in RCEMAP. The power turbine is fed from a hot gas plenum of known constant conditions while the compressor discharges into a compressed-air plenum having a known constant pressure. TMFT then determines the turbomachinery airflow and other operating conditions in accordance with the plenum conditions, turbomachinery maps and related inputs.

In order to use these two routines to simulate a complete, turbocharged rotary engine, several steps must be taken. These are: 1) The inlet plenum of RCTC must be identified as the compressed air receiver of TMFT; 2) The exhaust plenum of RCTC must be identified as the hot gas plenum that drives the turbine of TMFT; and 3) The airflow produced by TMFT must be equal to that demanded by RCTC. As with other versions of RCEMAP, an iterative matching procedure is required since the plenum conditions are not independent, but rather are implicitly defined by conditions in both TMFT and RCTC. Again the technique of Picard iteration is used to produce a self-consistent matched solution. That is, an initial trial solution is assumed; this consists of values for the following variables: air flow rate; fuel flow rate; engine exhaust gas temperature; engine inlet pressure; engine inlet temperature; and engine exhaust temperature. As previously noted, these variables are collected in the file RT.DAT. The initial values are used as inputs to TMFT and then RCTC. These routines return updated variable values which are recycled to be the next set of inputs, and soforth. When the change between successive iterations becomes smaller than some predetermined magnitude, the process is considered to have converged.

As mentioned in Section A-1, a DOS batch file known as REBAT.BAT is used together with some small auxiliary routines and data files to mechanize the process outlined above. Listings of the indicated code are tabulated below.

Table A-4.1: Batch File REBAT.BAT

```
ECHO OFF
PATH C:;C:\DOS\
ECHO: THIS FILE RUNS TMFT & RCTC IN SUCCESSION & DISPLAYS THE RESULTS.
REM
COPY RT.STA RT.DAT
ECHO: FIRST, DISPLAY THE INITIAL DATA.
TYPE RT.DAT
ECHO: THEN, ZERO OUT THE DATA IN THE PREVIOUS-STEP ARRAY ( RT.OLD )
ECHO: BY RUNNING CINIT.
CINIT
ECHO: FINALLY, DELETE THE RT.CON FILE SO THAT ITS EXISTENCE CAN BE USED
ECHO: LATER AS A CONVERGENCE TEST.
DEL RT.CON
:AGAIN
ECHO: RUNNING TMFT.
TMFT
TYPE RT.DAT
ECHO: RUNNING RCTC.
RCTC
TYPE RT.DAT
REM
ECHO: NOW RUN CTEST TO EXAMINE ERROR CONDITIONS.
CTEST
TYPE RT.DLT
COPY RT.DAT RT.OLD
IF EXIST RT.CON GOTO ENDING
GOTO AGAIN
:ENDING
TYPE RT.CON
```

Table A-4.2: Listing of CINIT

```
$NOFLOATCALLS
      PROGRAM CINIT
C
      DIMENSION ERV(6)
      DO 1 I = 1 , 6
      ERV(I) = 0.0
    1 CONTINUE
      K = 0
      OPEN ( UNIT = 10, FILE = 'RT.OLD' , STATUS = 'NEW' )
      WRITE ( 10 , 101 )  (ERV(J) , J = 1 , 6 ) , K
      CLOSE ( UNIT = 10 )
      STOP
  101 FORMAT (6(2X,F8.3),2XI2)
      END
```

Table A-4.3: Listing of CTEST

```
C
      PROGRAM CTEST
C
      DIMENSION ERR(7)
C
      OPEN ( UNIT = 9, FILE = 'RT.DAT', STATUS = 'OLD' )
      READ (9 , 101 ) AIR , FUEL , TEXH , PIM , RTIM , PEM , L
      CLOSE ( UNIT = 9 )
C
      OPEN ( UNIT = 10, FILE = 'RT.OLD', STATUS = 'OLD' )
      READ (10 , 101 ) AIRO , FUELO , TEXHO , PIMO , RTIMO , PEMO , K
C
      CLOSE ( UNIT = 10 )
C
      K = K + 1
      L = K
      OPEN ( UNIT = 9 , FILE = 'RT.DAT', STATUS = 'NEW' )
      WRITE ( 9 , 101 )AIR, FUEL, TEXH, PIM, RTIM, PEM, L
      CLOSE ( UNIT = 9 )
      OPEN ( UNIT = 10, FILE = 'RT.OLD', STATUS = 'NEW' )
      WRITE ( 10 , 101 )AIRO,FUELO,TEXHO,PIMO, RTIMO,PEMO,K
      CLOSE ( UNIT = 10 )
      IF ( K . GE . 8 ) GO TO 10
      ERR(1) = (AIR - AIRO ) / AIR
      ERR(2) = (FUEL - FUELO ) / FUEL
      ERR(3) = (TEXH - TEXHO ) / TEXH
      ERR(4) = (PIM - PIMO ) / PIM
      ERR(5) = (RTIM - RTIMO ) / RTIM
      ERR(6) = (PEM - PEMO ) / PEM
      ESQ = 0.
      DO 1 I = 1 , 6
      ESQ = ESQ + ERR(I)**2
    1 CONTINUE
      ERR(7) = SQRT ( ESQ )
      IF ( ERR(7) . GE . 1.E-4 ) GO TO 100
   10 CONTINUE
C
C     CONVERGENCE OR COUNT-OUT HAS BEEN ATTAINED.
C
      OPEN ( UNIT = 12, FILE = 'RT.CON',STATUS = 'NEW' )
      WRITE (12,103) ERR(7),K
  100 CONTINUE
      OPEN ( UNIT = 11, FILE = 'RT.DLT',STATUS = 'NEW' )
```

```
      WRITE (11,102) (ERR(J) , J = 1 , 7) , K
      STOP
  101 FORMAT (6(2X,F8.3), 2XI2 )
  102 FORMAT (7(1X,E9.3), 2XI2 )
  103 FORMAT (1XE9.3, 2XI2 )
      END
```

The auxiliary routine CINIT initializes the values in the file RT.OLD to zero. CTEST computes error components and a normalized error criterion, tests for convergence and writes output files RT.OLD, RT.DLT and RT.CON. REBAT.BAT first calls CINIT to zero out RT.OLD and then deletes the file RT.CON, so that it's existence can be used later to indicate that convergence has been attained. Next, REBAT calls TMFT, displays RT.DAT, calls RCTC, again displays RT.DAT, calls CTEST to examine the error conditions, displays RT.DLT, loads RT.OLD and finally tests the existence of RT.CON. If the test is negative, REBAT recycles to the point where TMFT is called and the remainder of the process is repeated. If RT.CON is found to exist, the process is considered to have converged, and the output files such as RCE1.OUT and RSHORT.OUT will contain data representing a matched case. The following table illustrates one example of the convergence process from an arbitrary set of initial values.

Table A-4.4: Convergence Summary

AIR	FUEL	TEXH	PIM	RTIM	PEM	K
1890.000	60.000	900.000	2.500	350.000	1.850	*
1795.394	58.255	981.775	2.249	363.657	1.819	1
1930.799	60.410	968.329	2.372	371.632	1.808	2
2028.231	62.491	970.652	2.515	379.056	1.896	3
2117.585	65.092	971.053	2.640	385.459	1.960	4
2142.070	66.033	974.868	2.693	387.699	2.016	5
2160.767	66.498	975.150	2.721	389.189	2.032	6
2160.854	66.625	976.664	2.730	389.689	2.048	7
"	"	"	"	"	"	"

* denotes initial data

B APPENDIX B: FORMULATION

The authors intend this section for the reader searching for more detailed descriptions of the models and sub-models employed by the RCEMAP. After a list of symbols, the first two segments of the formulation section detail how gases flow into and out of the combustion chamber via intake and exhaust ports and leakage and crevice flows. The next two segments detail calculation of losses, including heat transfer, friction and ancillary losses. Following the losses sections, the fundamental equations for the combustion chamber as a zero-dimensional well mixed control volume are presented. Finally, manifold and turbomachinery models are described.

B-1 Lists of Symbols, Subscripts and Superscripts

Table III-1: List of Symbols

Symbol	Description
a	Heat transfer expression constant
A	Area
b	Heat transfer expression constant
B_M	Nucleate boiling constant
	$B_M = 1.89 \times 10^{-14}$ in SI units
	$B_M = 2.13 \times 10^{-5}$ in USCS units
c_1, c_2	Heat transfer expression constants
c_d	Discharge coefficient
c_l	Liquid specific heat
c_p	Specific heat at constant pressure
C_{boil}	Nucleate boiling expression constant
d	Chamber depth or diameter
e	Specific internal energy
g	Gravitational acceleration
g_c	USCS units correction factor
G	Fluid mass velocity
h	Heat transfer coefficient
i	Specific enthalpy
i_{fg}	Latent heat of evaporation
k	Thermal conductivity
l	Material layer thickness
m	Mass
N	Engine speed (rpm)
N_u	Nusselt number
P	Pressure
P_r	Prandtl number
$\wp$	Power
q''	Heat flux
r_r	Rotor radius
R	Gas constant

R_e	Reynolds number
s	Distance along a seal path
T	Temperature
U	Overall heat transfer coefficient
v	Velocity
W	Work
$\bar{v}$	Mean velocity
V	Volume
x	Mass fraction
α	Heat transfer expression constant
δ	Seal depth
γ	Specific heats ratio
θ	Crank angle
Λ	Stoichiometric fuel/air mass ratio
μ	Dynamic viscosity
ν	Kinematic viscosity
ϕ	Equivalence ratio
φ	Apex seal lean angle
ρ	Density
σ	Surface tension
τ	Combustion expression decay constant

B-2 Intake and Exhaust

Both intake and exhaust flows are quasi-one-dimensional and compressible. When the ports are not choked and there is no backflow, mass flow rate through the intake and exhaust ports are given by equations 1 and 2, respectively.

$$\dot{m}_{int} = c_{d,int}\, A_{int}\, \rho_{im} \sqrt{\frac{2\,\gamma_{im}\, R_{im}\, T_{im}}{\gamma_{im}-1}\left[\left(\frac{P_{im}}{P_c}\right)^{\frac{2}{\gamma_{im}}} - \left(\frac{P_{im}}{P_c}\right)^{\frac{\gamma_{im}+1}{\gamma_{im}}}\right]} \tag{1}$$

$$\dot{m}_{exh} = c_{d,exh}\, A_{exh}\, \rho_c \sqrt{\frac{2\,\gamma_c\, R_c\, T_c}{\gamma_c-1}\left[\left(\frac{P_c}{P_{em}}\right)^{\frac{2}{\gamma_c}} - \left(\frac{P_c}{P_{em}}\right)^{\frac{\gamma_c+1}{\gamma_c}}\right]} \tag{2}$$

In equations 1 and 2, $\dot{m}$ is mass flow rate, c_d is discharge coefficient, A is port open area, ρ is density, γ is specific heats ratio, R is the gas constant, T is temperature, P is pressure, subscripts int and exh denote intake and exhaust, subscript c denotes combustion chamber and subscripts im and em denote intake and exhaust manifold properties.

When the ports are choked, intake and exhaust flow rates are:

$$\dot{m}_{int} = c_{d,int}\, A_{int}\, \rho_{im} \sqrt{\gamma_{im}\, R_{im}\, T_{im}}\left(\frac{2}{\gamma_{im}+1}\right)^{\frac{\gamma_{im}+1}{2(\gamma_{im}-1)}} \tag{3}$$

$$\dot{m}_{exh} = c_{d,exh}\, A_{exh}\, \rho_c \sqrt{\gamma_c\, R_c\, T_c}\left(\frac{2}{\gamma_c + 1}\right)^{\frac{\gamma_c+1}{2(\gamma_c-1)}} \tag{4}$$

Ports open linearly with crank angle until fully open, then close linearly with crank angle until fully closed as shown in Figure III-1. On Figure III-1, θ_{ipo} and θ_{ipc} are the crank angles at which the intake port begins to open and is fully closed, respectively. The crank angle increment before the port opens fully is $\Delta\theta_{ip}$. Similarly for the exhaust port, θ_{epo}, θ_{epc} and $\Delta\theta_{ep}$ are opening angle, closing angle and opening increment. Though the port areas and shapes vary during intake and exhaust, constant discharge coefficients are employed.

B-3 Leakage and Crevices

The calculation of leakage and crevice flows was adapted from Norman (9). For comparison, the reader may refer to the model and results of Eberle and Klomp (16). As shown in Figure III-2, Norman's model lumps leakage and crevice flows at the apex seals, so there are two direct leakage paths (lead and lag) and potentially two crevices (lead and lag) per chamber. The crevice mass "belongs" to the chamber whose pressure is highest. For example, if pressure P_1 in Figure III-2 is greater than P_2, the crevice "belongs" to chamber 1.

Leakage Leakage flow takes place through a fixed, user-specified area, A_{leak}. In the past, this area has been estimated based on static tests on pressurized engines. An alternate approach is to adjust A_{leak} to match calculated engine pressures to observed engine pressures. Leakage flow is quasi-one-dimensional and compressible and depends on the difference in pressure on the two sides of the apex seal. The composition, pressure and temperature of the leakage mass are the same as crevice volume properties, since the leaked gases are near the tip region of the rotor. For $P_1 > P_2$, leakage flow through the leakage path of Figure III-2 is approximated by:

$$\dot{m}_{leak} = c_d\, A_{leak}\, \rho_{crev} \sqrt{\frac{2\,\gamma_{crev}\, R_{crev}\, T_{crev}}{\gamma - 1}\left[\left(\frac{P_1}{P_2}\right)^{\frac{2}{\gamma}} - \left(\frac{P_1}{P_2}\right)^{\frac{\gamma+1}{\gamma}}\right]} \tag{5}$$

when the flow is not choked and

$$\dot{m}_{leak} = c_d\, A_{leak}\, \rho_{crev} \sqrt{\gamma_{crev}\, R_{crev}\, T_{crev}}\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \tag{6}$$

when flow is choked. In equations 2 and 3, c_d is the leakage path discharge coefficient, ρ is density, γ is the specific heats ratio, R is the gas constant, T is the temperature and subscript *crev* denotes a thermodynamic property of the crevice gas. Leakage path discharge coefficient is equal to 1.0.

Crevices Each apex seal has one crevice belonging to the adjacent chamber with the higher pressure. At any instant, crevice pressure, temperature and composition are uniform. Crevice pressure is a function of crank angle. Crevice temperature and volume are fixed during the cycle. Crevice volume should be based on engine measurements and crevice temperature equals rotor temperature. The ideal gas relation, applied to the crevice volume, yields

$$m_{crev} = \frac{P_{crev}\, V_{crev}}{R_{crev}\, T_{crev}} \tag{7}$$

where V_{crev} is crevice volume. Equation 4 is differentiated with respect to time for:

$$\frac{\dot{m}_{crev}}{m_{crev}} = \frac{\dot{P}_{crev}}{P_{crev}} - \frac{\dot{R}_{crev}}{R_{crev}} \tag{8}$$

In the DISC RCE, very little fuel or burnt products should reach the rotor tip region, so the change in crevice composition during the cycle is small. Consequently,

$$\dot{m}_{crev} = \left(\frac{\dot{P}_{crev}}{P_{crev}}\right) m_{crev} \tag{9}$$

B-4 Heat Transfer

Two questions must be addressed to calculate engine heat transfer: what is the hot-gas-side heat transfer coefficient and what are the trochoid housing, side housing and rotor face temperatures.

Hot-gas-side heat transfer coefficient According to Woschni (6), heat transfer in an intermittent combustion engine is characterized by two phases: heat transfer during combustion and heat transfer without combustion. In the absence of combustion, the bulk gas velocity is proportional to the mean rotor velocity. Mean rotor velocity, $\bar{v}_{rotor}$, is

$$\bar{v}_{rotor} = \frac{\pi\, N\, r_r}{90} \tag{10}$$

where N is engine speed (in rpm) and r_r is the rotor radius. Non-firing velocity is then

$$v_{non-firing} = c_1\, \bar{v}_{rotor} \tag{11}$$

and c_1 is a constant. During combustion, burning gas expands rapidly and its velocity relative to the rotor and housings increases. Consequently, an extra term appears in the expression for bulk gas velocity. During combustion, bulk gas velocity is

$$v_{firing} = c_1\, v_{non-firing} + c_2 \left(\frac{V_c}{V_{ipc}}\right)\left(\frac{T_{ipc}}{P_{ipc}}\right)(P_c - P_{non-firing}) \tag{12}$$

where c_2 is a constant, V is volume, T is temperature, P is pressure, subscript c denotes combustion chamber conditions and subscript ipc denotes conditions when the intake port closes. Constants c_1 and c_2 are program inputs and are determined best by comparing predicted and observed heat transfer rates. $P_{non-firing}$ is calculated assuming isentropic compression and expansion and knowing P_{ipc}. The authors performed calculations replacing the Woschni combustion term in (12) with a term proportional to the burning rate as calculated by Raju (17). The resulting heat transfer coefficient profiles matched Raju's profiles (predicted by a 3-dimensional internal flow model) than those predicted using equation 12; Woschni's model results in overprediction of heat transfer coefficient away from TDC since pressure falls more slowly than burning rate. Thses results are currently unpublished. Because these changes were not deemed mature, they were deleted from the program for the time being.

Woschni postulated that heat transfer in the combustion chamber is similar to forced convection over a flat plate. Therefore he used the expression

$$N_u = \alpha\, R_e{}^a\, P_r{}^b \tag{13}$$

for Nusselt number, N_u. In Equation 13, α, a and b are constants, R_e is Reynolds number and P_r is Prandtl number. Norman (9) set Prandtl equal to one, leaving

$$N_u = \alpha\, R_e{}^a \tag{14}$$

To flesh out equation 14, the definitions of Nusselt number, Reynolds number and Prandtl number with respect to the rotary engine combustion chamber are provided below.

$$N_u = \frac{h_{hg}\, d}{k_{hg}} \tag{15}$$

$$R_e = \frac{v\, d}{\nu_{hg}} \tag{16}$$

$$P_r = \frac{\mu_{hg}\, c_{p,hg}}{k_{hg}} \tag{17}$$

In equations (15) – (17), h is heat transfer coefficient, d is chamber depth, k is thermal conductivity, v is appropriate gas velocity (either firing or non-firing), ν is kinematic viscosity, μ is dynamic viscosity, c_p is specific heat at constant pressure and subscript hg denotes a property of the hot chamber gases. The transport properties are calculated according to the method presented by Mansouri and Heywood (18).

This completes the discussion of hot-gas-side heat transfer coefficient calculation. Two other papers dealing with rotary engine heat transfer are found in the open literature. Lee et al. (19) formulated relations for forced convection heat transfer in a DISC RCE based on experimental temperature measurements. Atesmen (20) analyzed heat transfer in the rotary engine using one-dimensional and two-dimensional quasi-steady models, and used a two-dimensional transient model to analyze heat transfer at a position in the trochoid housing subject to high thermal stress.

Component temperatures In addition to hot-gas-side heat transfer coefficient, **RCEMAP** requires the rotor, trochoid housing and side housing surface temperatures for heat transfer calculations. These temperatures are either assigned or calculated.

The quickest, dirtiest way to fix component surface temperatures is to assign the components temperatures and hold them fixed. Next in complexity, the user inputs temperatures corresponding to 30 housing and rotor positions in the cycle, as proposed by Stanton (11). This is more realistic, since, for example, the area around the spark plug is always hotter than the area around the intake port. However, short of guessing, the user must have component temperature data to assign realistic temperatures. If the user chooses to assign temperatures in RCEMAP, temperatures are assigned to the midpoints of 30 crank angle partitions. The first partition begins when the intake port opens (θ_{ipo}) and lasts for 36°. The user assigns housing and rotor temperature at the segment midpoint, meaning the first temperature is assigned at $\theta_{ipo} + 18°$, the second at $\theta_{ipo} + 54°$, the third at $\theta_{ipo} + 90°$ and so on. Temperatures between segment midpoints are interpolated.

Rather than assign housing and rotor temperatures, RCEMAP can calculate component temperatures internally based on quasi-steady, one-dimensional heat transfer through the component walls. Figure II-6 shows heat transfer path through a component material and the equivalent thermal resistance network. In the MIT code, the components are made of one, two or three materials, each with its own thickness, l_1, l_2 and l_3, and thermal conductivity, k_1, k_2 and k_3. Average hot-gas-side heat transfer coefficient and gas temperature are $\bar{h}_{hg}$ and $\bar{T}_{hg}$ and coolant-side heat transfer coefficient and temperature are h_{cool} and T_{cool}. The overall heat transfer coefficient, U, corresponding to the thermal network of Figure II-6 is

$$U = \frac{1}{\frac{1}{h_{hg}} + \frac{l_1}{k_1} + \frac{l_2}{k_2} + \frac{l_3}{k_3} + \frac{1}{h_{cool}}} \tag{18}$$

or, from the hot-gas-side surface to the coolant,

$$U^* = \frac{1}{\frac{l_1}{k_1} + \frac{l_2}{k_2} + \frac{l_3}{k_3} + \frac{1}{h_{cool}}} \tag{19}$$

Surface temperature is assumed steady at any location and calculated by equating hot-gas-side heat transfer to coolant-side heat transfer.

$$\bar{h}_{hg} A_w (\bar{T}_{hg} - T_w) = U^*(T_w - T_{cool}) \tag{20}$$

In Equation 20, A_w is the the hot-gases/component-surface interface area and T_w is the component surface temperature. Equation 20 is solved for component surface temperature, yielding

$$T_w = \frac{\bar{h}_{hg}\bar{T}_{hg} + U^* T_{cool}}{U^* + \bar{h}_{hg}} \tag{21}$$

Wall temperature is calculated for each trochoid housing and side housing segment midpoint. The average hot-gas-side heat transfer coefficient and temperature are calculated as follows.

$$\bar{h}_{hg} = \frac{\int_0^{\theta_i} h_{hg}\, d\theta - \int_0^{\theta_{i+1}} h_{hg}\, d\theta}{\theta_{i+1} - \theta_i} \tag{22}$$

$$\bar{T}_{hg} = \frac{\int_0^{\theta_i} T_{hg}\, d\theta - \int_0^{\theta_{i+1}} T_{hg}\, d\theta}{\theta_{i+1} - \theta_i} \tag{23}$$

In Equations 22 and 23, θ_i and θ_{i+1} are segment beginning and ending crank angles.

A single rotor face temperature is used during the engine cycle. It is calculated at the end of each engine cycle based on heat transfer coefficient and temperature averaged over the entire cycle (i.e., $\theta_i = 0°$ and $\theta_{i+1} = 1080°$ in Equations 22 and 23).

Cooling Coolant side heat transfer coefficient, h_{cool}, is estimated differently for the rotor cavity, the side housing and the trochoid housing. The inner wall of the rotor face is cooled by oil droplets splashing against the inner wall and draining away. Since this oil splashing process does not vary during the cycle and the fluid inside the rotor cavity is not subject to changes in chamber pressure and temperature, the coolant-side heat transfer coefficient should remain constant throughout the cycle. The oil cooling in the rotor cavity is similar to "cocktail shaker" cooling in sodium filled valves. "Cocktail shaker" cooling is described by Bush and London in reference (21).

The side housings are cooled via conduction through the parts of the side housing not in contact with the hot gases and by natural convection on the housing outer wall. A constant, user-input coolant-side heat transfer coefficient is used as the side housing boundary condition.

Liquid flows through passages running along the depth of the trochoid housing for cooling. The cooling liquid might undergo nucleate boiling near the hottest spots on the housing. Consequently, The prediction of heat transfer rates in the cooling passages follows the analysis presented by Rohsenow et al. (22). In the absence of nucleate boiling, heat transfer is characterized as forced convection in the tubes:

$$q''_{FC} = h_{cool}(T_w - T_b) \tag{24}$$

In equation 24, q''_{FC} is the forced convection heat flux from the liquid to the tube wall, T_w is the tube wall temperature, T_b is the bulk liquid temperature and h_{cool} is given by:

$$h_{cool} = 0.023 \left(\frac{k_b}{d_h}\right) \left(\frac{G\, d_h}{\mu_f}\right)^{4/5} \left(\frac{\mu_f\, c_{p,b}}{k_b}\right)^{1/3} \tag{25}$$

where k is thermal conductivity, d_h is the tube hydraulic diameter, G is the fluid mass velocity (fluid mass flow rate divided by tube cross sectional area), μ is the liquid kinematic viscosity and c_l is the liquid specific heat. Subscript b denotes a property evaluated at the bulk liquid temperature and subscript f denotes a property evaluated at the film temperature: $T_f = 0.5 \times (T_b + T_w)$.

The expression for heat flux is formidable when nucleate boiling is included. Assuming the presence of bubbles near the tube wall does not influence fluid properties too much and assuming the cooling liquid does not undergo a very large change in temperature, heat flux to the tube walls from the coolant is

$$q'' = \sqrt{\left(q''_{FC}\right)^2 + \left(q''_B\right)^2} \tag{26}$$

In equation 26, the additional heat flux due to low quality boiling, q''_B, is given by

$$q''_B = B_M \frac{(g/g_c)^{\frac{1}{2}}\, i_{fg}^{\frac{1}{8}}\, k_l^{\frac{1}{2}}\, \rho_l^{\frac{17}{8}}\, c_l^{\frac{19}{8}}\, \rho_g^{\frac{1}{8}}\, (T_{ts} - T_{sat})^3}{\sigma^{\frac{9}{8}}\, (\rho_l - \rho_g)^{\frac{5}{8}}\, T_{sat}^{\frac{1}{8}}} \tag{27}$$

where $B_M = 1.89 \times 10^{-14}$ in SI units, $B_M = 2.13 \times 10^{-5}$ in USCS units, g is gravitational acceleration, $g_c = 1$ for SI units, $g_c = 32.174 \frac{\mathrm{ft\,lb_m}}{\mathrm{lb_f\,s}}$ for USCS units, i_{fg} is the latent heat of evaporation, k is thermal conductivity, ρ is density, c is specific heat, T is temperature, σ is surface tension, subscripts l and g denote saturated liquid and gas states of the coolant liquid and subscript ts denotes properties at the coolant tube surface. In practice, many of the constants and properties of equation 28 are lumped into one constant, C_{boil}, which is assumed approximately the same in all the cooling passages. Equation 27 becomes

$$q''_B = C_{boil}\,(T_{ts} - T_{sat})^3 \tag{28}$$

To calculate tube wall temperature, heat flux to the tube walls from the coolant (equation 26) is set equal to heat flux to the tube walls from the hot gases:

$$q'' = U^*\,(\bar{T}_{hg} - T_{ts}) \tag{29}$$

where U^* is the overall heat transfer coefficient from the hot gases to the coolant tube surface.

B-5 Friction and Ancillary Losses

Four separate calculations are made for rotary engine friction losses: the apex seals friction; the side seals friction; the oil ring seals friction; and the ancillary losses (other than seal friction).

Apex seals Rachel (14) improved the apex seal friction model of Vilman et al. (23). The apex seal is subject to an inertial force, a centrifugal force, gas pressure forces, a spring force and slot friction forces, as diagrammed on Figure III-3. On Figure III-3 the rotor is rotating clockwise, φ is the lean angle (between the apex seal and a line perpendicular to the trochoid housing at the point of contact, b_a is the apex seal base dimension, a_r is the seal tip radius of curvature, P_1 is the chamber pressure in the chamber lagging the seal and P_2 is the lead chamber pressure. Because $P_2 > P_1$, the apex seal of Figure III-3 is pushed to the slot's left side.

The normal force the apex seal exerts on the trochoid housing is

$$F_{N,a} = l_a \left(\frac{b_a}{2} + a_r \sin\varphi \right) + m_a\, \ddot{\theta}^2 \left[\frac{R}{9} + \epsilon \cos\left(\frac{2\theta}{3}\right) \right] -$$

$$\zeta_a\, m_a\, \ddot{\theta}^2 \sin\left(\frac{2\theta}{3}\right) - \zeta_a\, P_h\, (\delta_a - c_a)\, l_a -$$

$$\zeta_a\, \delta_a\, \Delta P\, (c_a - a_r + a_r \cos\varphi) + F_{s,a} \tag{30}$$

where l_a is the seal length ("into" the trochoid housing), ϵ is the rotor eccentricity, θ is the crank angle, ζ_a is the sliding coefficient of friction between the apex seal and trochoid housing, $\zeta_{a.s}$ is the coefficient of friction between the apex seal and seal slot, m_a is the apex seal mass, P_h is the higher of P_1 and P_2, ΔP equals $\mid P_2 - P_1 \mid$, δ_a is the apex seal height (base to tip), c_a is the difference between the seal height, δ, and the slot depth. $F_{s,a}$ is the spring force exerted on the apex seal base and, finally, φ is the apex seal lean angle, where

$$\varphi = \arccos \left\{ \frac{3\epsilon \cos\left[\frac{2}{3}(\theta + 180^\circ)\right] + r_r}{\sqrt{9\epsilon^2 + r_r^2 + 6\,\epsilon\, r_r \cos\left[\frac{2}{3}(\theta + 180^\circ)\right]}} \right\} \tag{31}$$

The apex seal follows an irregular path around the crank center. The apex seal speed as a function of crank angle is

$$\frac{ds_a}{d\theta} = \sqrt{\epsilon^2 + \frac{r_r^2}{9} + \frac{2}{3}\,\epsilon\, r_r \cos\left(\frac{2\theta}{3}\right)} \tag{31}$$

where s_a is the distance the apex seal moves from crank angle 0° to crank angle θ. The work resulting from the apex seal friction force traversing the seal path for an entire cycle is

$$W_{f,a} = \int_0^{6\pi} F_{f,a} \frac{\overline{ds_a}}{d\theta}\, d\theta \qquad (32)$$

Side seals Since the inertial forces on the seals do not influence their normal force on the side housings, side seal friction is easier to analyze. Figure III-4 shows a side seal schematic and free body diagram. Forces on the side seal include gas pressure force, spring force, slot friction force and normal force from the side housing. The normal force the side seal exerts on the side housing is

$$F_{N,s} = F_{s,s} + (b_s - \zeta_s\, \delta_s)\, l_s\, P_c(\theta) \qquad (33)$$

In equation 33, $F_{s,s}$ is the side seal spring force, b_s is the seal seal base dimension, ζ_s is the sliding coefficient of friction between the side seal and side housing, δ_s is the side seal base-to-top dimension, $P_c(\theta)$ is the chamber pressure at crank angle θ and l_s is the side seal length, given by

$$l_s = 2\, r_s \arcsin\left(\frac{\sqrt{3}\, R}{2\, r_s}\right) \qquad (34)$$

and

$$r_s = \frac{r_r^2 - 2\,\epsilon\, r_r + 4\,\epsilon^2}{r_r - 4\,\epsilon} \qquad (35)$$

The side seal friction force is

$$F_{f,s} = \zeta_s\, F_{s,N} \qquad (36)$$

The work associated with side seal friction is found by approximating the friction force as all residing at the seal midpoint and integrating the friction force and the distance the side seal center moves for an entire cycle. The side seal center's speed can be shown to be

$$\frac{ds_{ss}}{d\theta} = \sqrt{\left(\frac{r_r}{2} - 3\epsilon\right)^2 \cos\theta + \frac{r_r^2}{36} - \frac{r_r}{3}\left(\frac{r_r}{2} - 3\epsilon\right)\cos\left(\frac{2\,\theta}{3}\right)} \qquad (37)$$

and to find the work, the following integration is performed:

$$W_{f,s} = \int_0^{6\pi} F_{f,s} \frac{ds_{ss}}{d\theta}\, d\theta \qquad (38)$$

Oil seals Figure III-5a shows a cross section of the oil seal and Figure III-5b shows a segment of the oil seal from a top-view. The incremental normal force the oil ring segment segment exerts on the side housing has components due to the crank case pressure and the oil seal spring.

$$dF_{N,o} = P_{cc}\, b_o\, R_o\, \frac{1}{3}\, d\theta + F_{s,o} \tag{39}$$

In equation 39, P_{cc} is the crank case pressure, b_o is the oil seal base dimension, R_o is the oil seal radius and $F_{s,o}$ is the oil seal spring force. The incremental oil seal friction force due to the seal segment is

$$dF_{f,o} = \mu_o\, P_{cc}\, b_o\, R_o\, \frac{1}{3}\, d\theta + \mu_o\, F_{s,o} \tag{40}$$

To include all oil seal segments, the incremental force, $dF_{f,o}$, is integrated over 6π crank angle radians (recall, the crank turns three times faster than the oil seal):

$$F_{f,o} = 2\pi\, \mu_o\, P_{cc}\, b_o\, R_o\, + \mu_o\, F_{s,o} \tag{41}$$

In one cycle, the oil seal rotates one full turn and moves hoola-hoop like around the crank center three times. The oil seal friction work, therefore, has two parts. The vector giving the oil seal center position, $\vec{r_o}$ is

$$\vec{r_o} = \langle -\epsilon \cos\theta,\ \epsilon \sin\theta \rangle \tag{42}$$

and the speed the oil seal center travels is

$$\frac{ds_c}{d\alpha} = \sqrt{\epsilon^2 \sin^2\theta + \epsilon^2 \cos^2\theta} = \epsilon \tag{43}$$

Where s_c is the distance the oil seal travels. Over one cycle, the oil seal center travels the distance

$$s_c = \int_0^{6\pi} \frac{ds_c}{d\theta}\, d\theta = 6\pi\, \epsilon \tag{44}$$

The distance each oil seal segment moves during one rotation is $2\pi\, r_o$. The work to overcome oil seal friction is therefore

$$W_{f,o} = F_{f,o}\,(2\pi\, r_o + 6\pi\, \epsilon) \tag{45}$$

Ancillary Losses As noted by Assanis et al. (24), friction mean effective contributions fall into three groups: (i) losses due to boundary lubrication, (ii) losses associated with hydrodynamically lubricated surfaces in relative motion and (iii) pumping losses. Boundary lubrication losses are invariant with speed and have a strong dependence on compression ratio. Hydrodynamic lubrication losses vary directly with engine speed. Pumping losses are the most dependent on speed and vary with its square. Milligan and Hartles (25), based on the three loss groups above, proposed the following expression for friction mean effective pressure ($fmep$):

$$fmep = L_1 + 7\left(\frac{N}{1000}\right) + 1.5\left(\frac{S_p}{1000}\right)^2 \tag{46}$$

where L_f is a constant equal to compression ratio minus four for a direct injection Diesel engine, N is engine speed in rpm and S_p is mean piston speed in $\frac{\text{ft}}{\text{min}}$. **RCEMAP** employs an expression similar to equation 46 for ancillary losses, but for completeness' sake, several other models are presented below.

VanGerpen (26) proposed the following expression for $fmep$ for a Diesel engine simulation:

$$\frac{fmep}{\rho_o \bar{v}_p^2} = \frac{6.2 \times 10^4 \, C_r^{0.2}}{R_e} \tag{47}$$

where ρ_o is oil density, $\bar{v}_p$ is mean piston speed, C_r is compression ratio and R_e is Reynolds number based on the bore and using oil viscosity:

$$R_e = \frac{\rho_o \, \bar{v}_p \, B}{\mu_o} \tag{48}$$

An expression used by Harris and Youssef (27) for turbocompound Diesel engines looks similar to equation 46. They use the expression

$$fmep = 0.894 + 0.04137 \, \bar{v}_p + 0.0017496 \, \bar{v}_p^2 \tag{49}$$

where $\bar{v}_p$ should be in $\frac{\text{m}}{\text{sec}}$ and the resulting $fmep$ is in bars.

Originally, Bartrand and Willis (12) proposed the expression

$$fmep_a = C_{A1}^* + C_{A2}^* \left(\frac{N}{1000}\right)^2 \tag{50}$$

for $fmep$ due to ancillary losses. The linear term in equation 46 was left out, since seal and bearing friction were calculated explicitly and added to $fmep_a$ separately. In equation (50), N is engine speed in rpm and C_{A1}^* and C_{A2}^* are constants. Based on examination of motored engine friction data, Hoque (14) recommended adding a linear term to the ancillary $fmep$ expression. Therefore, in **RCEMAP**

$$fmep_a = C_{A1} + C_{A2} \left(\frac{N}{1000}\right) + C_{A3} \left(\frac{N}{1000}\right)^2 \tag{51}$$

where C_{A1}, C_{A2} and C_{A3} are all constants whose values are best ascertained by analysis of motored engine $fmep$ data.

B-6 The DISC RCE Combustion Chamber

Gases inside the RCE combustion chamber are treated as an open thermodynamic system whose contents have a uniform temperature, pressure and composition at any instant. This zero-dimensional model is shown schematically in Figure II-4. Only the events in one chamber (referred to as the chamber of interest) are modeled during the cycle simulation. However, because each chamber undertakes the same processes, conditions in the unmodeled chambers are estimated from stored data for the chamber of interest. In Figure II-4, the rotor rotates in a clockwise direction and the dashed line is a control volume about the chamber of interest.

In the basic formulation, conservation of mass, species and energy are applied to the open system of Figure II-4, along with the ideal gas relation. A synopsis of the basic formulation is presented below and was adapted from Norman (9), Roberts (10) and Stanton (11).

Conservation of mass Gases enter or exit the system via the intake port (labeled a on Figure II-4), the exhaust port (b), the leakage path (c), the crevice flow (d) or the fuel injector (e). Although leakage occurs along all side seals and apex seals and crevice flows occur along side seals, in apex seal slots and in injector and spark plug holes, leakage and crevice flows are lumped at the apex seals. Provisions were made for backflow of chamber contents into the intake port and reverse flow from the exhaust port to the chamber.

Conservation of mass is written:

$$\frac{dm_c}{dt} = \dot{m}_c = \dot{m}_{int} - \dot{m}_{exh} + \dot{m}_{leak} + \dot{m}_{crev} + \dot{m}_{fuel} \tag{52}$$

In equation 52, mass flow into the chamber is positive, m_c is the mass inside the control volume, m_{int} is mass through the intake port, m_{exh} is mass through the exhaust port, m_{leak} is mass leaked past the seals, m_{crev} is crevice mass flow, m_{fuel} is the rate gaseous fuel is added to the chamber mass and a dot over a variable denotes derivative with respect to time. Explicit formulations of intake, exhaust, fuel flow, leakage and crevice flow rates can be found above.

Conservation of Species Three "species" are considered inside the combustion chamber: unburned air, burnt products and burnt fuel. Burned products include burned air and fuel and unburned air is everything else. Burned fuel is a useful fictitious quantity whose mass is the same as the mass of all the fuel burned during the cycle. Burned products mass fraction and burned fuel mass fraction are related by $x_f = \left(\frac{\Lambda}{1+\Lambda}\right) x_b$ where Λ is the stoichiometric fuel/air mass ratio. Fuel does not enter the control volume in the RCEMAP model until it is burned; unburned gaseous fuel is not considered a constituent of the chamber gases.

Burned products and fresh air are depleted/increased in the system by mass flows over the control volume boundaries and by combustion. The conservation of burnt fuel mass is written:

$$\dot{m}_f = \dot{m}_{f,int} + \dot{m}_{f,exh} + \dot{m}^{lead}_{f,crev} + \dot{m}^{lag}_{f,crev} + \dot{m}^{lead}_{f,leak} +$$

$$\dot{m}^{lag}_{f,leak} - \dot{m}_{f,burned} \tag{53}$$

In equation 53, subscript f denotes fuel, int denotes intake, exh denotes exhaust, $crev$ denotes crevice flow, $leak$ denotes leakage flow, b denotes burnt fuel and superscripts $lead$ and lag denote the lead and lag crevice and leakage flows. Each term in equation 53 will be fleshed out separately below. The fuel burn rate term, $\dot{m}_{f,burned}$ is discussed in the combustion section of the report.

The relations for fuel fuel flow through the ports depend on the flow direction. Intake and exhaust fuel flows are given by

$$\dot{m}_{f,int} = \begin{cases} x_{f,im}\,\dot{m}_{int} & \text{when } \dot{m}_{int} \geq 0; \\ x_f\,\dot{m}_{int} & \text{when } \dot{m}_{int} < 0. \end{cases} \tag{54}$$

$$\dot{m}_{f,exh} = \begin{cases} x_f\,\dot{m}_{exh} & \text{when } \dot{m}_{exh} \geq 0; \\ x_{f,em}\,\dot{m}_{exh} & \text{when } \dot{m}_{exh} < 0. \end{cases} \tag{55}$$

The fuel flow rate for the crevice and leakage flows are also dependent on the flow direction. Let $\dot{m}_f^{lead} = \dot{m}_{f,crev}^{lead} + \dot{m}_{f,leak}^{lead}$ and $\dot{m}_f^{lead} = \dot{m}_{f,crev}^{lead} + \dot{m}_{f,leak}^{lead}$. Lead and lag crevice and leakage fuel flows are then

$$\dot{m}_{f,crev}^{lead} = \begin{cases} x_{f,crev}^{lead}\,\dot{m}_f^{lead} & \text{when } \dot{m}_f^{lead} \geq 0; \\ x_f\,\dot{m}_f^{lead} & \text{when } \dot{m}_f^{lead} < 0. \end{cases} \tag{56}$$

$$\dot{m}_{f,crev}^{lag} = \begin{cases} x_{f,crev}^{lag}\,\dot{m}_f^{lag} & \text{when } \dot{m}_f^{lag} \geq 0; \\ x_f\,\dot{m}_f^{lag} & \text{when } \dot{m}_f^{lag} < 0. \end{cases} \tag{57}$$

In RCEMAP, the fuel mass fraction, fresh air mass fraction and burnt products mass fraction define the combustion chamber composition. Combustion chamber fuel mass fraction, $x_f = m_f/m_c$, changes with respect to time according to the relation

$$\dot{x}_f = \frac{\dot{m}_f}{m_c} - x_f\,\frac{\dot{m}_c}{m_c} \tag{58}$$

Rate of change of burnt products mass fraction, x_b, is

$$\dot{x}_b = \dot{x}_f \left(\frac{\Lambda + 1}{\Lambda}\right) \tag{59}$$

where Λ is the stoichiometric fuel/air mass ratio. Rate of change of fresh air mass fraction is

$$\dot{x}_a = -\dot{x}_b \tag{60}$$

and rate of change of the equivalence ratio, ϕ, is

$$\dot{\phi} = \frac{1}{\Lambda}\frac{\dot{x}_f}{(1 - x_f)^2} \tag{60}$$

Combustion Gatowski et al. (3) plotted combustion heat release rates (based on chamber pressure data) versus crank angle in an attempt to model DISC combustion. They theorized that DISC combustion takes place in two stages: combustion heat release rate rises linearly to some maximum value, then falls exponentially. The two stages are shown in Figure II-5. In the first stage, combustion heat release rate follows the relation

$$\frac{dQ_c}{d\theta} = \left(\frac{dQ_c}{d\theta}\right)_{max} \left(\frac{\theta - \theta_s}{\theta_m - \theta_s}\right) \tag{61}$$

and in the second phase

$$\frac{dQ_c}{d\theta} = \left(\frac{dQ_c}{d\theta}\right)_{max} e^{\frac{-(\theta-\theta_m)}{\tau}} \tag{62}$$

In equations 61 and 62, Q_c is fuel energy, θ_s is the crank angle when ignition begins, θ_m is the crank angle at which the maximum fuel energy release rate occurs, $\left(\frac{dQ_c}{d\theta}\right)_{max}$ is the maximum heat release rate and τ is the combustion rate decay constant. Program inputs are θ_s, θ_m and $\left(\frac{dQ_c}{d\theta}\right)_{max}$ and the fraction of fuel that burns, X_c.

To obtain a decay constant expression, the heat release rate (equation 61) is integrated from θ_s to θ_m and the heat release rate of equation 62 is integrated from θ_m to ∞. The resulting integrated heat releases are set equal to the total fuel energy liberated in combustion. Since the fuel does not burn fully, the fuel energy, $m_f \times LHV$, is scaled by an efficiency, X_c. The resulting expression for decay constant is

$$\tau = \frac{X_c\,(m_{f,cycle} \times LHV)}{\left(\frac{dQ_c}{d\theta}\right)_{max}} - \tfrac{1}{2}(\theta_m - \theta_s) \tag{63}$$

Where $m_{f,cycle}$ is the total amount of fuel injected per cycle. As explained above, fuel is not considered part of the chamber gases until it vaporizes and burns. The fuel burning rate is:

$$\dot{m}_{f,burned} = \frac{m_{f,cycle} \times \left(\frac{dQ_c}{d\theta}\right)}{m_f \times LHV} \tag{64}$$

<u>Ideal Gas Relation</u> The ideal gas relation provides an expression for the change in chamber pressure with respect to time. Differentiating the ideal gas relation with respect to time yields

$$\dot{P}_c = P_c\left(\frac{\dot{R}_c}{R_c} + \frac{\dot{m}_c}{m_c} + \frac{\dot{T}_c}{T_c} - \frac{\dot{V}_c}{V_c}\right) \tag{65}$$

The change in gas constant with respect to time, $\dot{R}_c$, should only be a function of composition. To this end, rate of change of density is expressed as

$$\dot{\rho}_c = \left(\frac{\partial \rho_c}{\partial T_c}\right)_{P_c,\phi} \dot{T}_c + \left(\frac{\partial \rho_c}{\partial P_c}\right)_{T_c,\phi} \dot{P}_c + \left(\frac{\partial \rho_c}{\partial \phi}\right)_{P_c,T_c} \dot{\phi} \tag{66}$$

where ϕ is equivalence ratio. For brevity, the subscripts on the partial derivatives of density will henceforth be omitted. The partial derivatives $\frac{\partial \rho_c}{\partial T_c}$ and $\frac{\partial \rho_c}{\partial P_c}$ are evaluated using the ideal gas relation and equation 66 becomes

$$\dot{\rho}_c = -\frac{P_c}{R_c T_c^2}\,\dot{T}_c + \frac{1}{R_c T_c}\,\dot{P}_c + \left(\frac{\partial \rho_c}{\partial \phi}\right)\dot{\phi} \tag{67}$$

Rate of change of the gas constant is

$$\dot{R}_c = \frac{1}{\rho_c T_c}\,\dot{P}_c - \frac{P_c}{\rho_c^2 T_c}\,\dot{\rho}_c - \frac{P_c}{\rho_c T_c^2}\,\dot{T}_c \tag{68}$$

Equation 67 is substituted into equation 68 for

$$\dot{R}_c = \frac{P}{\rho^2 T_c}\left(\frac{\partial \rho_c}{\partial \phi}\right)\dot{\phi} \tag{69}$$

Finally, substituting equation 69 into equation 65 yields an expression for the rate of change of chamber pressure:

$$\dot{P}_c = \frac{P_c}{\rho_c}\left(\frac{\partial \rho_c}{\partial \phi}\right)\dot{\phi} + \frac{P_c}{m_c}\,\dot{m}_c + \frac{P_c}{T_c}\,\dot{T}_c - \frac{P_c}{V_c}\,\dot{V}_c \tag{70}$$

Conservation of energy Energy crosses the boundary of the open thermodynamic system of Figure II-4 by means of intake flow, exhaust flow, leakage and crevice flows and combustion. The first law is applied to the combustion chamber control volume as

$$\dot{E}_c = \sum_{j=1}^{n_s} \dot{m}_j\, i_j - \dot{Q}_{ht} - \wp \tag{71}$$

where E is the control volume internal energy, n_s is the number of ways mass crosses system boundaries, i_j is enthalpy for stream j, $\dot{Q}_{ht}$ is the cooling energy loss rate and $\wp$ is the engine indicated shaft power (due to PdV work). Dots over quantities denote derivatives with respect to time. Next, chamber gas kinetic and potential energy are ignored and the left hand side of equation 71 is expanded and some manipulation is done.

$$\frac{d}{dt}(m_c i_c - P_c V_c) = \sum_{j=1}^{n_s} \dot{m}_j\, i_j - \dot{Q}_{ht} - \wp$$

$$\dot{m}_c i_c + m_c \dot{i}_c - \dot{P}_c V_c - P_c \dot{V}_c = \sum_{j=1}^{n_s} \dot{m}_j\, i_j - \dot{Q}_{ht} - P_c \dot{V}_c$$

$$m_c \dot{i}_c = \sum_{j=1}^{n_s} \dot{m}_j\, i_j - \dot{Q}_{ht} - P_c \dot{V}_c - \dot{m}_c i_c \tag{72}$$

Derivative of enthalpy is expressed in terms of its partial derivatives:

$$\dot{i}_c = c_p\,\dot{T}_c + c_t\,\dot{P}_c + c_\phi \dot{\phi} \tag{73}$$

Relations from equations 70 and 73 are used in equation 72. The result is an expression for rate of change of temperature:

$$\dot{T}_c = \frac{\sum_{j=1}^{n_s} \dot{m}_j\, i_j - \dot{Q}_{ht} - \dot{m}_c\, i_c + \left[\frac{\Upsilon}{\rho_c}\frac{\partial \rho_c}{\partial \phi}\,\dot{\phi} - m_c\, c_\phi\right]\dot{\phi} + \frac{\Upsilon}{m_c}\dot{m}_c - \frac{\Upsilon}{V_c}\dot{V}_c}{m_c\, c_p - \frac{\Upsilon}{T_c}} \tag{74}$$

where $\Upsilon = P_c\,(V_c - m_c\, c_t)$.

In summary, equations 52, 58, 70 and 74 make up the fundamental system equations for the conservation of mass, species and energy and the equation of state for the chamber of interest.

B-7 Manifolds

Intake and exhaust manifolds are modeled as well mixed control volumes whose thermodynamic properties are uniform and whose volumes are constant. Other modelers (7), (8), use one-dimensional manifold models. These models predict wave action in the manifolds and may allow more accurate volumetric efficiency prediction.

Intake manifold An intake manifold schematic is shown in Figure II-7a. In addition to the above assumptions, the intake manifold composition is not expected to change much during the cycle, so derivatives involving change in composition are neglected. Conservation of mass and energy and the ideal gas relation are applied to the intake manifold, resulting in the following relations for change in manifold mass, temperature and pressure:

$$\dot{m}_{im} = \dot{m}_{ac} - \dot{m}_{int} \tag{75}$$

$$\dot{T}_{im} = \left(\frac{T_{im}}{P_{im}\, V_{im}}\right)\left[\frac{\dot{m}_{ac}\,(i_{ac} - i_{im}) + R_{im}\, T_{im}\, \dot{m}_{im} + \dot{Q}_{im}}{\frac{c_{p.im}}{R_{im}} - 1}\right] \tag{76}$$

$$\dot{P}_{im} = P_{im}\left(\frac{\dot{m}_{im}}{m_{im}} + \frac{\dot{T}_{im}}{T_{im}}\right) \tag{77}$$

where $\dot{Q}_{im}$ is heat transfer through manifold walls, subscript im denotes an intake manifold property, subscript ac denotes the gas flowing from the aftercooler (or atmosphere) to the intake manifold and m_{int} is the mass through the engine intake port. Currently, heat transfer to intake manifold walls is assumed negligible.

Exhaust manifold The exhaust manifold formulation is nearly the same as the intake manifold's, except the manifold's composition varies with time, since the exhaust stream composition changes a great deal during the cycle. For example during blow-by a large amount of the exhaust gas is cool, fresh air, straight from the intake port, while during blow-down most of the gas is high pressure and temperature burnt products. Conservation of mass for the exhaust manifold is written

$$\dot{m}_{em} = \dot{m}_{exh} - \dot{m}_t \tag{78}$$

where m_t is manifold efflux to the turbine (or atmosphere).

Composition of the gases entering the exhaust manifold is frozen, leading to the following equation for rate of change of fresh air mass fraction in the exhaust manifold:

$$\dot{x}_{a,em} = \frac{\dot{m}_{exh}}{m_{em}} \left(x_{a,exh} - x_{a,em} \right) \tag{79}$$

where subscript a denotes fresh air. The first law, applied to the exhaust manifold, yields

$$\dot{T}_{em} = \frac{\dot{m}_{exh}(i_{exh} - i_{em}) - m_{em}(e_{a,em} - e_{b,em})\dot{x}_{a,em} + R_{em}T_{em}(\dot{m}_{exh} - \dot{m}_t) + \dot{Q}_{em}}{m_{em}\,(c_{p,em} - R_{em})} \tag{80}$$

where e is specific internal energy, $\dot{m}_{exh}$ is mass flow rate from the exhaust port to the exhaust manifold and subscript b denotes burnt gas properties. Finally, the ideal gas relation for the exhaust manifold contents takes the form

$$\dot{P}_{em} = P_{em} \left[\frac{\dot{m}_{em}}{m_{em}} + \frac{\dot{T}_{em}}{T_{em}} + \frac{\dot{x}_{a,em}\left(R_{a,em} - R_{b,em}\right)}{R_{em}} \right] \tag{81}$$

B-8 Turbomachinery

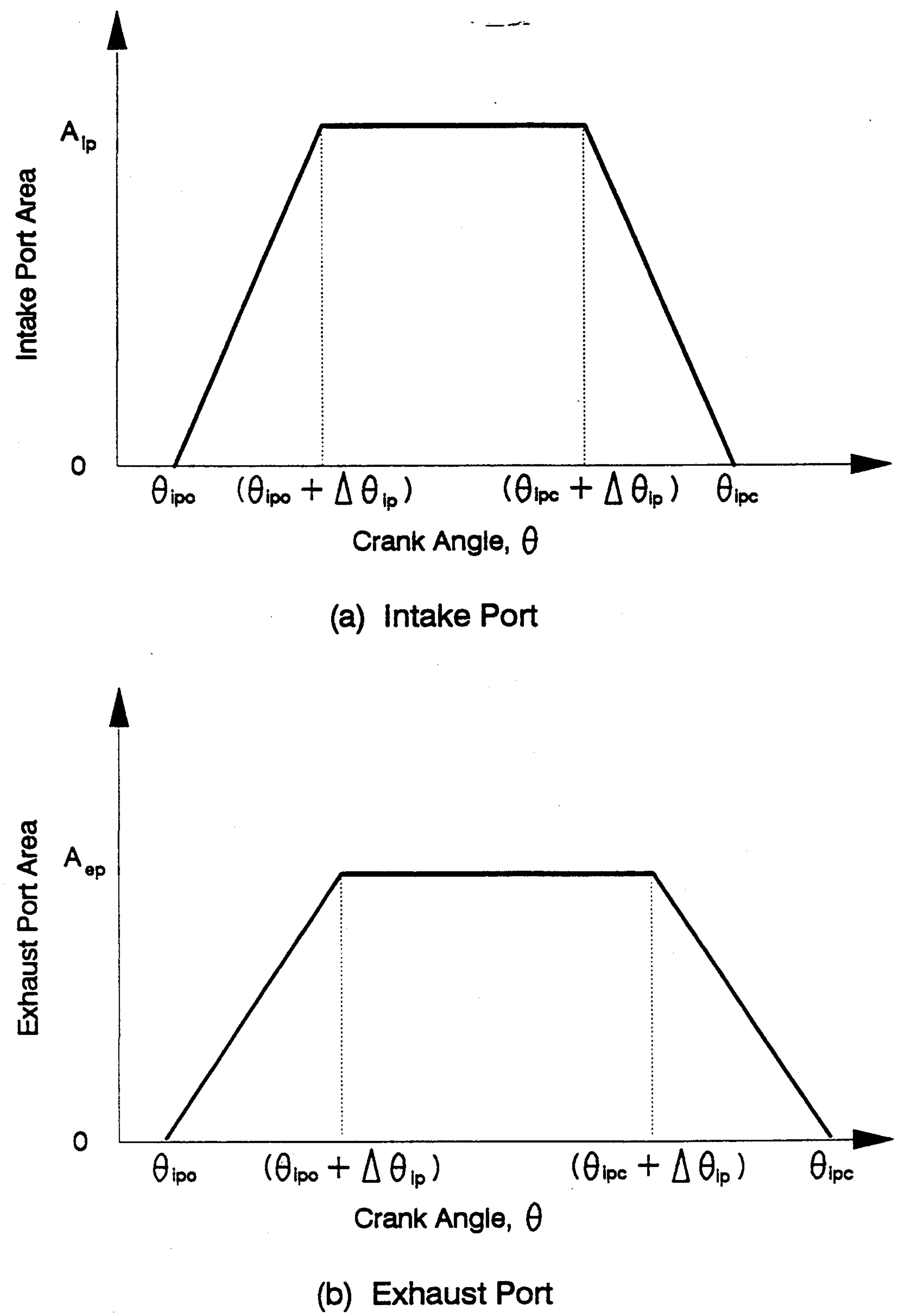
Two turbocharger options are available to **RCEMAP** users: the single spool one stage compression (conventional) turbocharger and the two-stage compression single spool turbocharger. For both turbochargers, the compressor(s) and turbine are all on the same shaft (and spin at the same actual speed).

Compressor and Turbine Maps Compressor and turbine performance is read from data maps, rather than calculated from first principles. There are two motivations for using maps: to make **RCEMAP** compatible with the NASA Navy Engineering Program (NNEP) turbocharged engine modeling program and because the complexities of modeling turbomachinery are beyond the scope of this program. Typical compressor maps are shown in Figure III-6. In Figure III-6(a), the solid lines correspond to constant corrected speed and the dashed lines are interpolating lines. Figure III-6(b) is a compressor efficiency map. Often compressor pressure ratio and efficiency maps are condensed into one map with speed lines, interpolating lines and islands of iso-efficiency.

The flow lines and efficiency lines are based on experimental data. The interpolating lines are drawn by the user according to the following rules: (1) interpolating lines should not cross (2) the values assigned to the interpolating lines are only relative; assign any value to the top interpolating line, then assign successively higher values to the others. The small solid circles form a grid of points for which the corrected flow, pressure ratio and efficiency are input to the program. More specific information on the necessary compressor map inputs is found in the inputs section of this report. Figure III-7 is a typical turbine map. Similar to the compressor map, corrected flow, compression ratio and efficiency are input to **RCEMAP** corresponding to the solid circles on the map.

Turbocharger Matching Compressor(s) and turbines are matched at the end of each RCEMAP engine cycle. For given air flow rate and exhaust temperature, turbocharger speed is varied until compressor required power and turbine available power match. Actual turbocharger speed is held constant during the cycle. An alternative to using compressor and turbine maps is presented by Heywood (2). He matches compressor and turbine by relating the difference in turbine and compressor output to a function of shaft rotational speed, turbocharger inertia and a rotational damping factor.

Pulsed Operation During the engine cycle, the turbocharger compressor and especially the turbine encounter a large range of inlet conditions, as shown on Figure III-8. Exhaust gas pressure and temperature both undergo large variations, as does the mass flow rate through the exhaust port. RCEMAP accounts for these variations by allowing the compressor and turbine operating points to shift. To account best for unsteady turbine performance, steady turbine maps should be extended to low mass flow regions and scaled to account for efficiency losses in unsteady operation. Kastner and Bhinder (28) proposed an algorithm for calculation of turbine performance at off-design conditions which might be used to extend and scale turbine maps.



(a) Intake Port

(b) Exhaust Port

Figure B-1: Intake and Exhaust Port Area Profiles

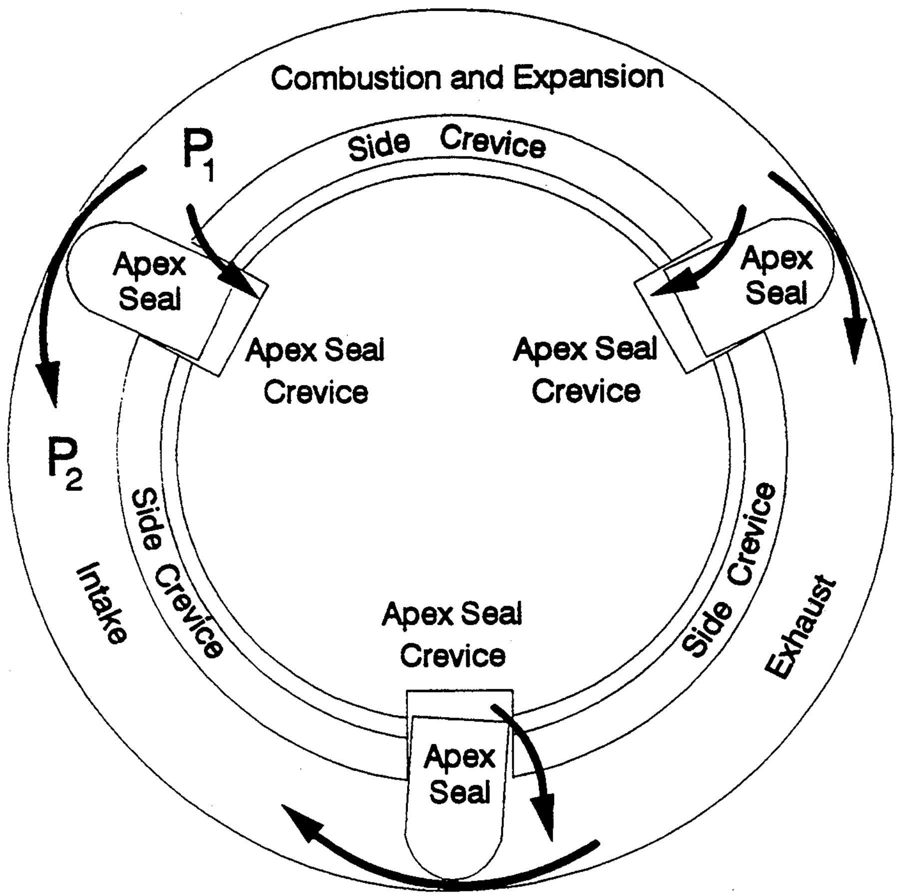
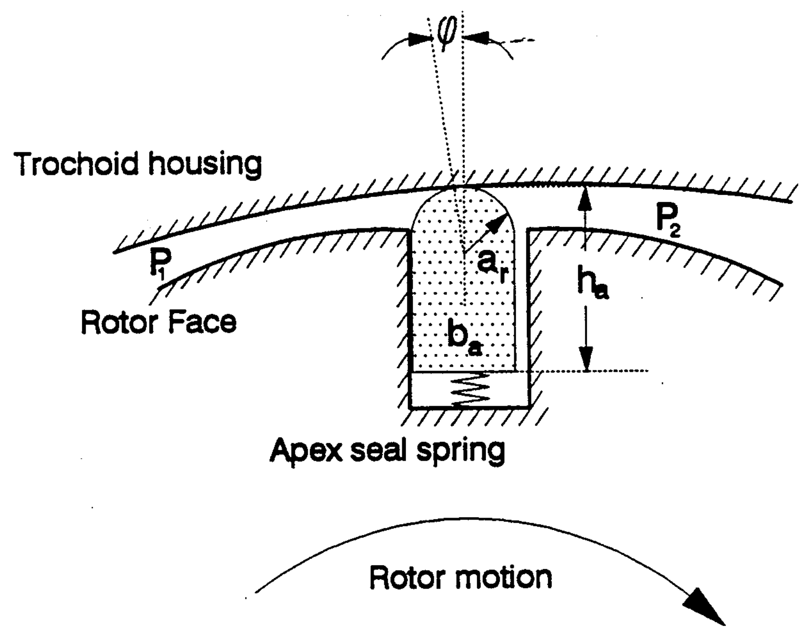
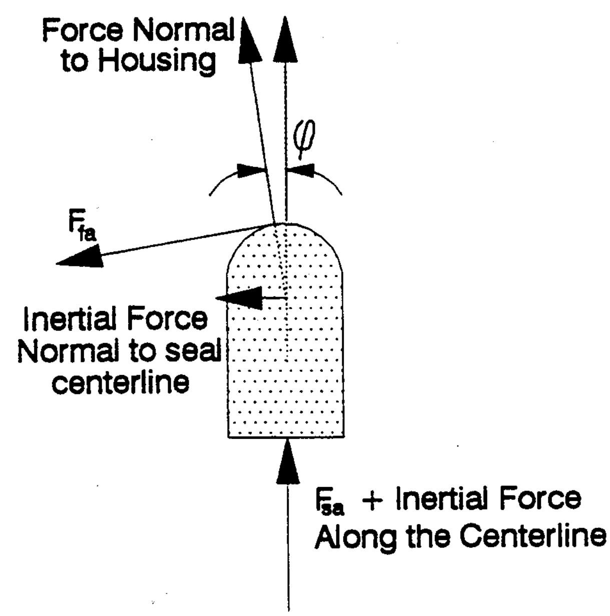


Figure B-2: Leakage and Crevice Model
(Figure adapted from Norman (11))

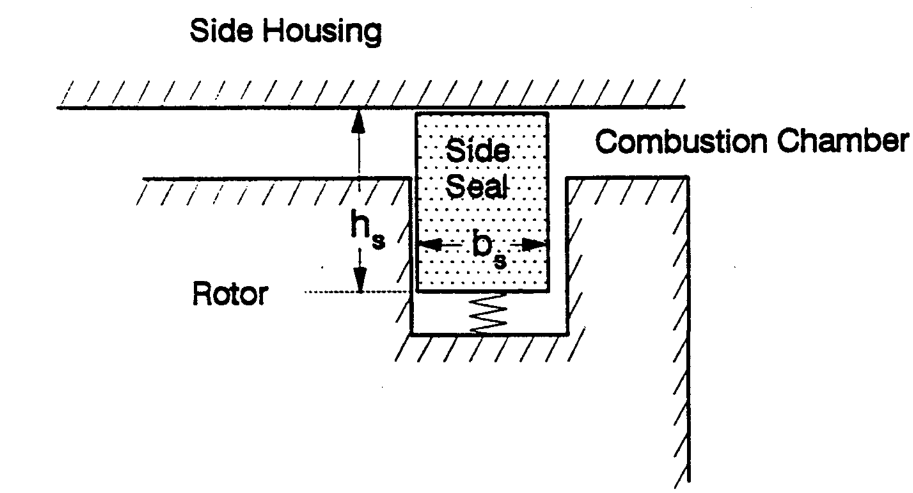


(a) Apex Seal Geometry

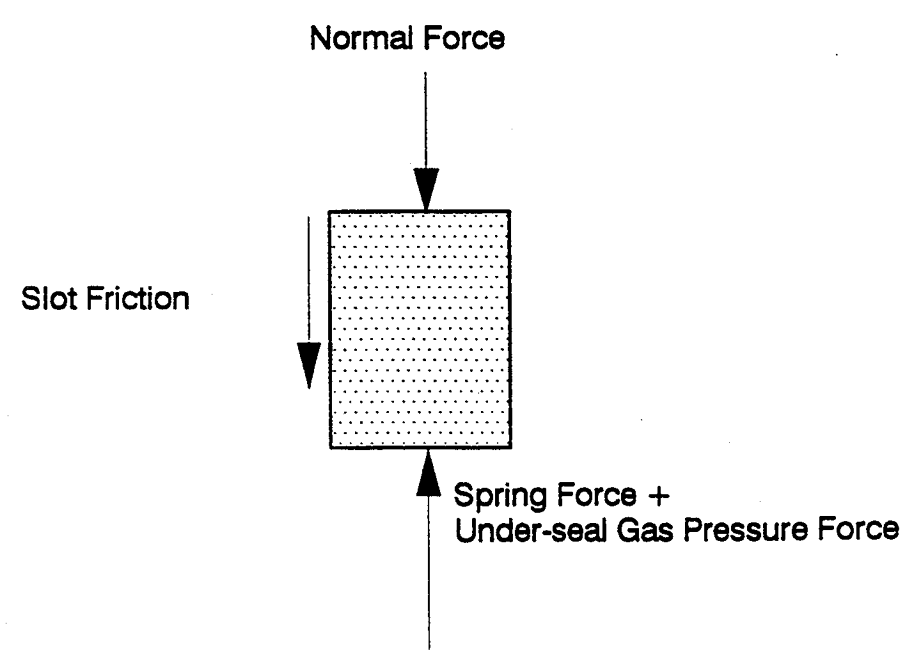


(b) Free Body Diagram

Figure B-3: Apex Seal Geometry and Free Body Diagram

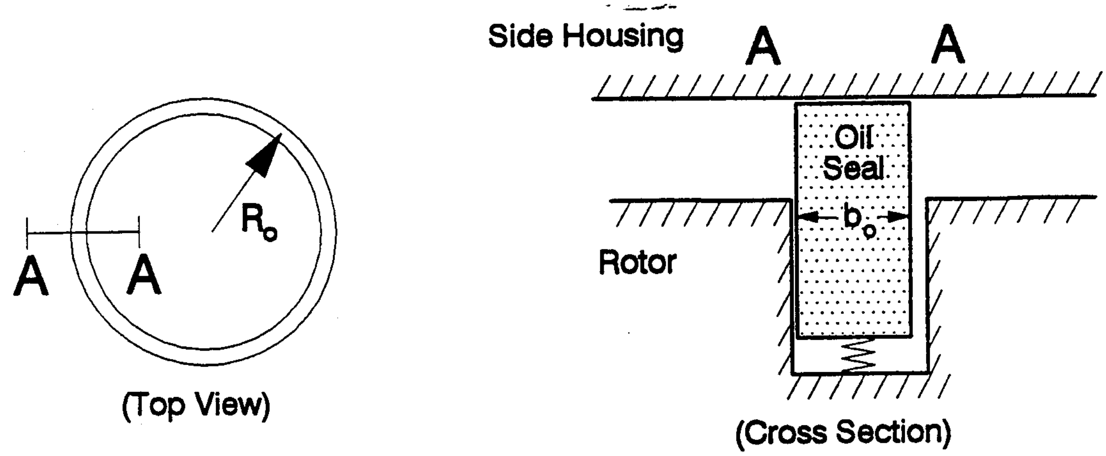


(a) Side Seal Geometry

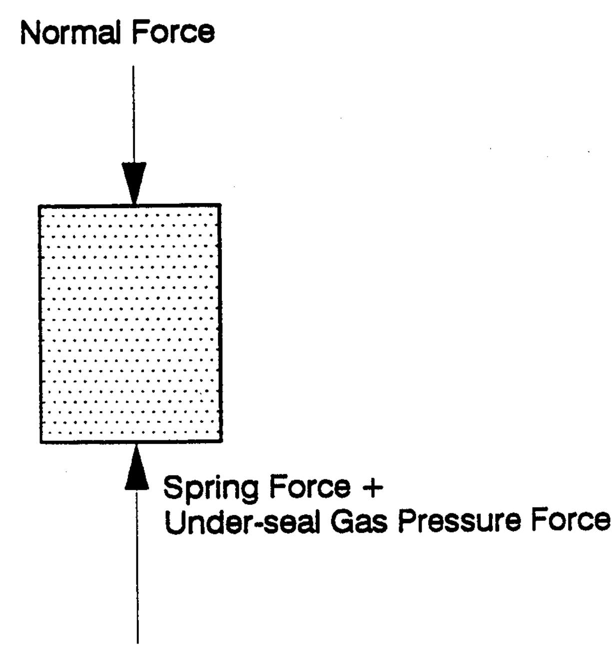


(b) Free Body Diagram

Figure B-4: Side Seal Geometry and Free Body Diagram

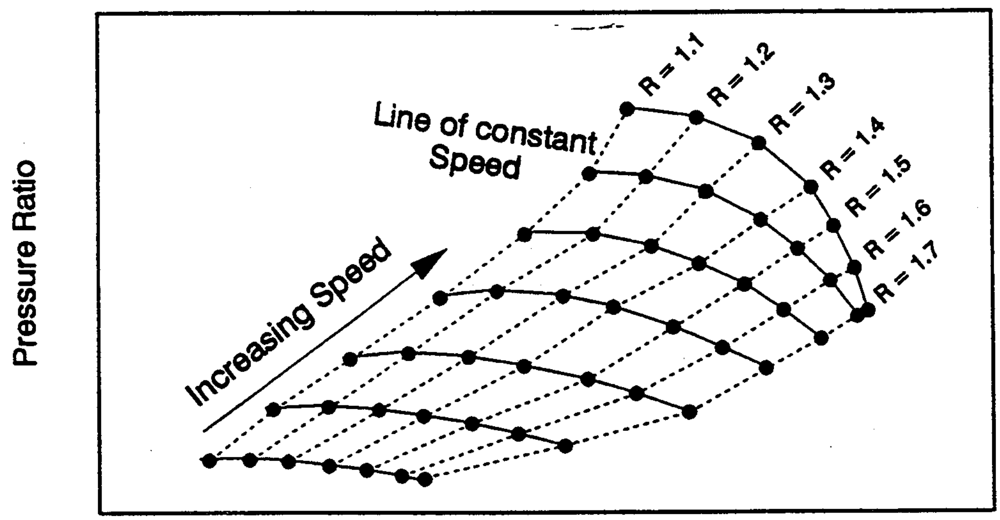


(a) Oil Seal Geometry

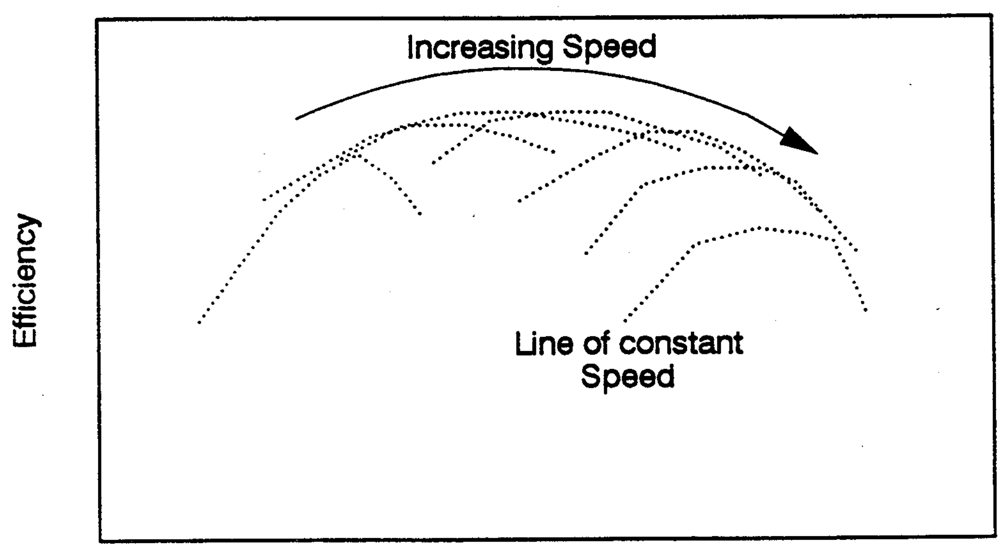


(b) Free Body Diagram

Figure B-5: Oil Seal Geometry and Free Body Diagram

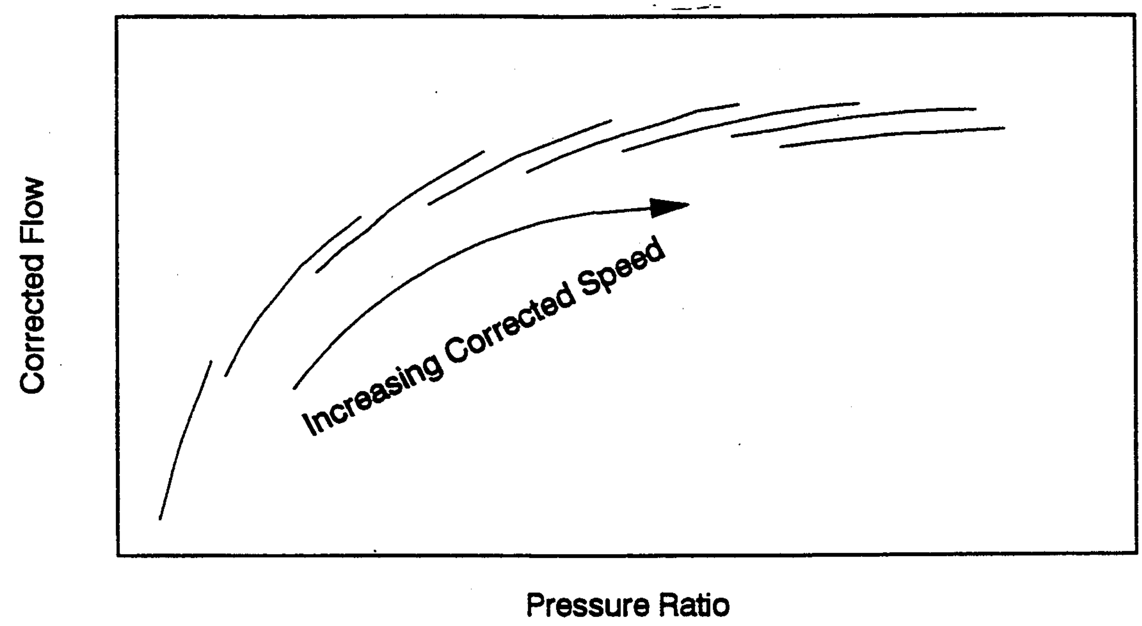


(a) Compressor Pressure Ratio Map

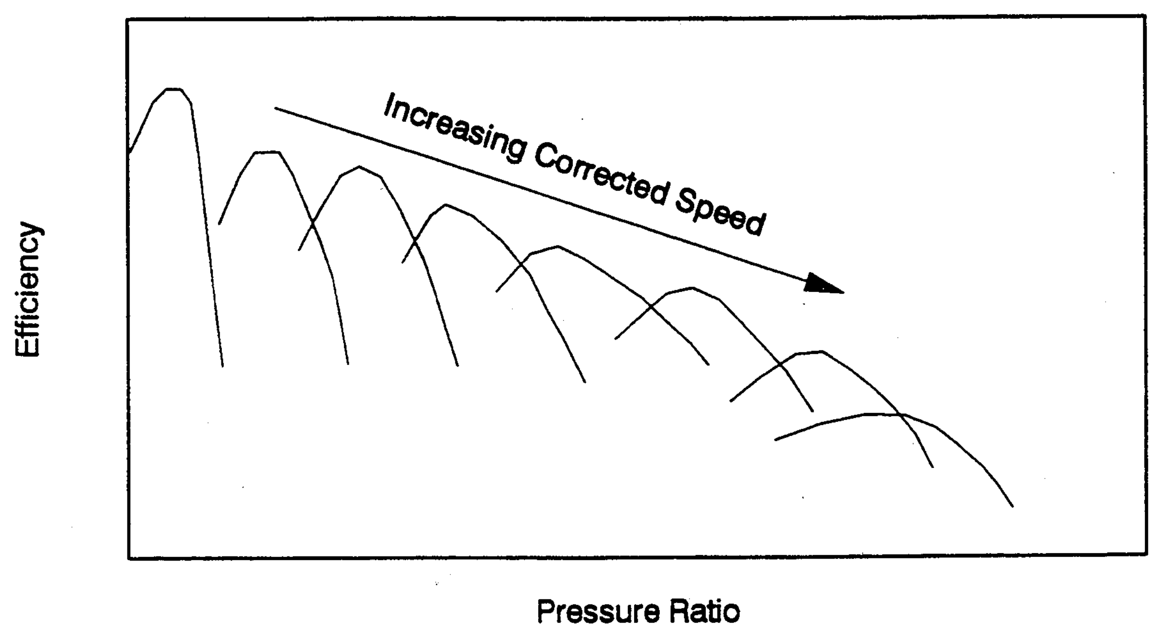


(b) Compressor Efficiency Map

Figure B-6: Typical Compressor Map



(a) Turbine Flow Rate Map



(b) Turbine Efficiency Map

Figure B-7: Typical Turbine Maps

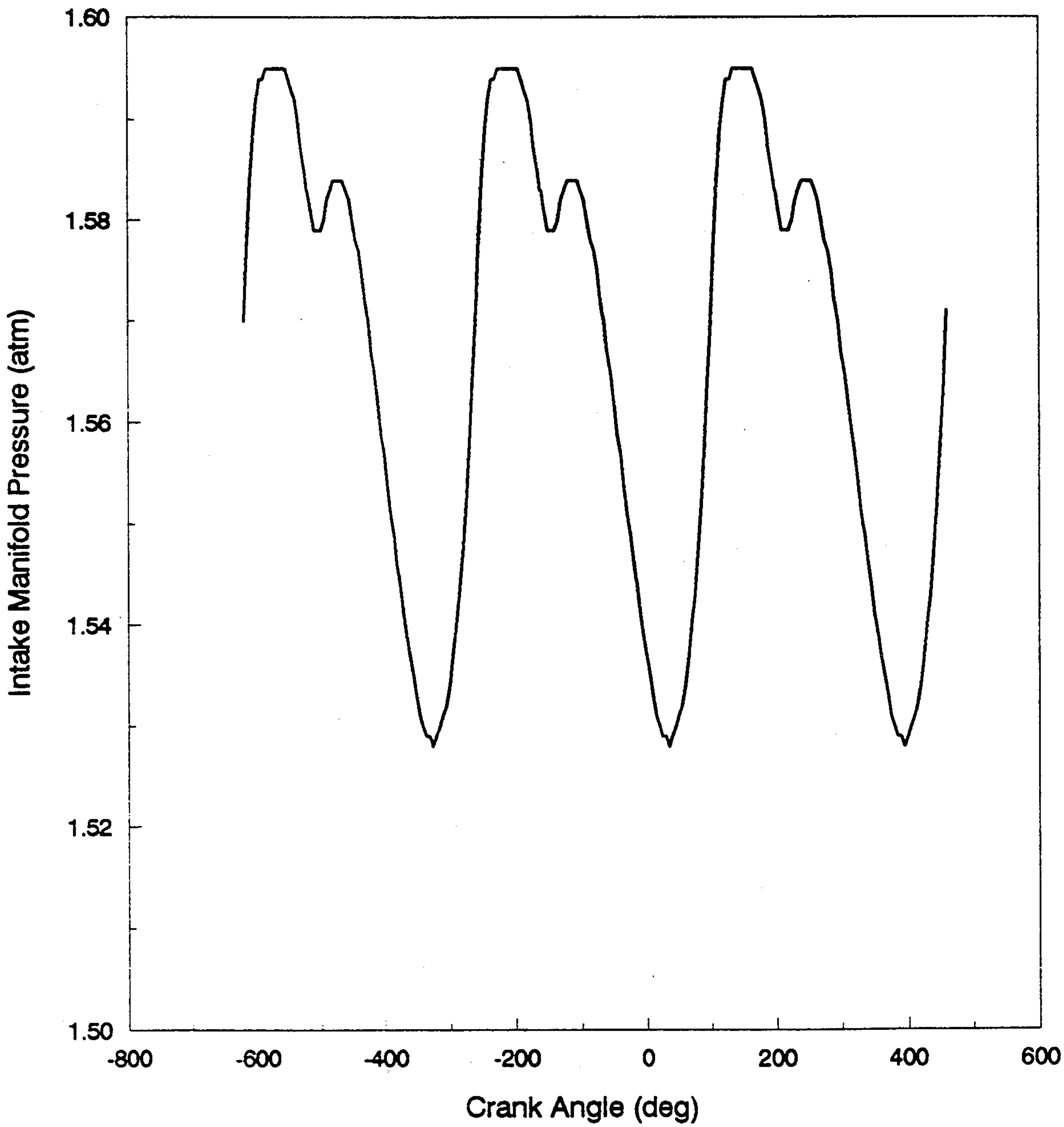


Figure B-8: Intake Manifold Pressure Pulses

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13. ABSTRACT *(Maximum 200 words)*

This report is a user's guide for a computer code that simulates the performance of several rotary combustion engine configurations. It is intended to assist prospective users in getting started with RCEMAP and/or RCEMAPPC. RCEMAP (Rotary Combustion Engine performance MAP generating code) is the mainframe version, while RCEMAPPC is a simplified subset designed for the personal computer, or PC, environment. Both versions are based on an open, zero-dimensional combustion system model for the prediction of instantaneous pressures, temperature, chemical composition and other in-chamber thermodynamic properties. Both versions predict overall engine performance and thermal characteristics, including bmep, bsfc, exhaust gas temperature, average material temperatures and turbocharger operating conditions. Required inputs include engine geometry, materials, constants for use in the combustion heat release model and turbomachinery maps. Illustrative examples and sample input files for both versions are included.

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